West Antarctic Surface Melt: Energy Budget, Meteorological Drivers, and Large-Scale Climate Forcing

Ryan Scott
Scripps Institution of Oceanography

CERES Science Team Meeting
May 8, 2019

West Antarctic Surface Melt: Energy Budget, Meteorological Drivers, and Large-Scale Climate Forcing

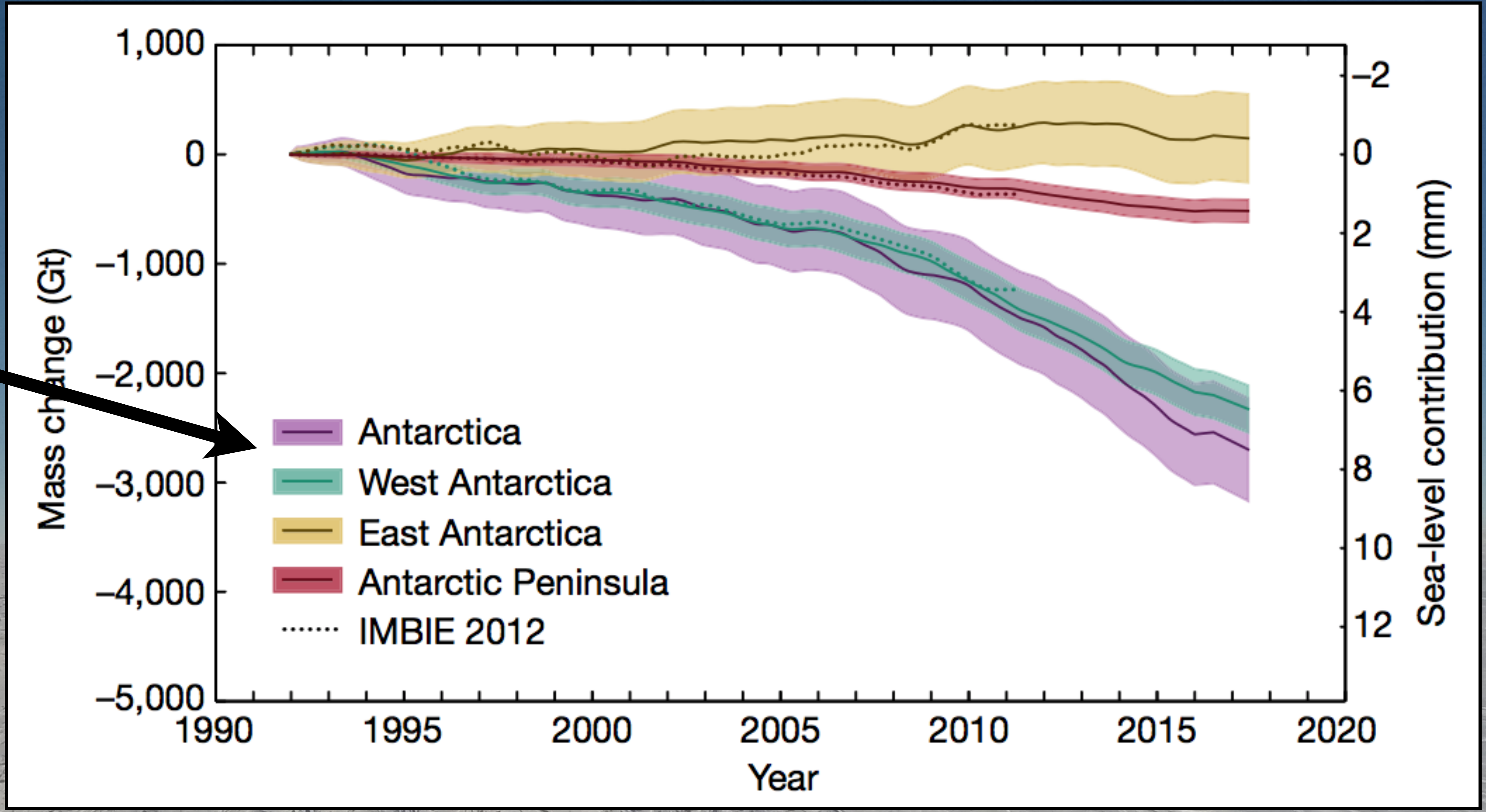
Ryan Scott
Scripps Institution of Oceanography

Coauthors: David Bromwich (Byrd Polar), Julien Nicolas (ECMWF), Joel Norris and Dan Lubin (SIO)

CERES Science Team Meeting
May 8, 2019

Motivation

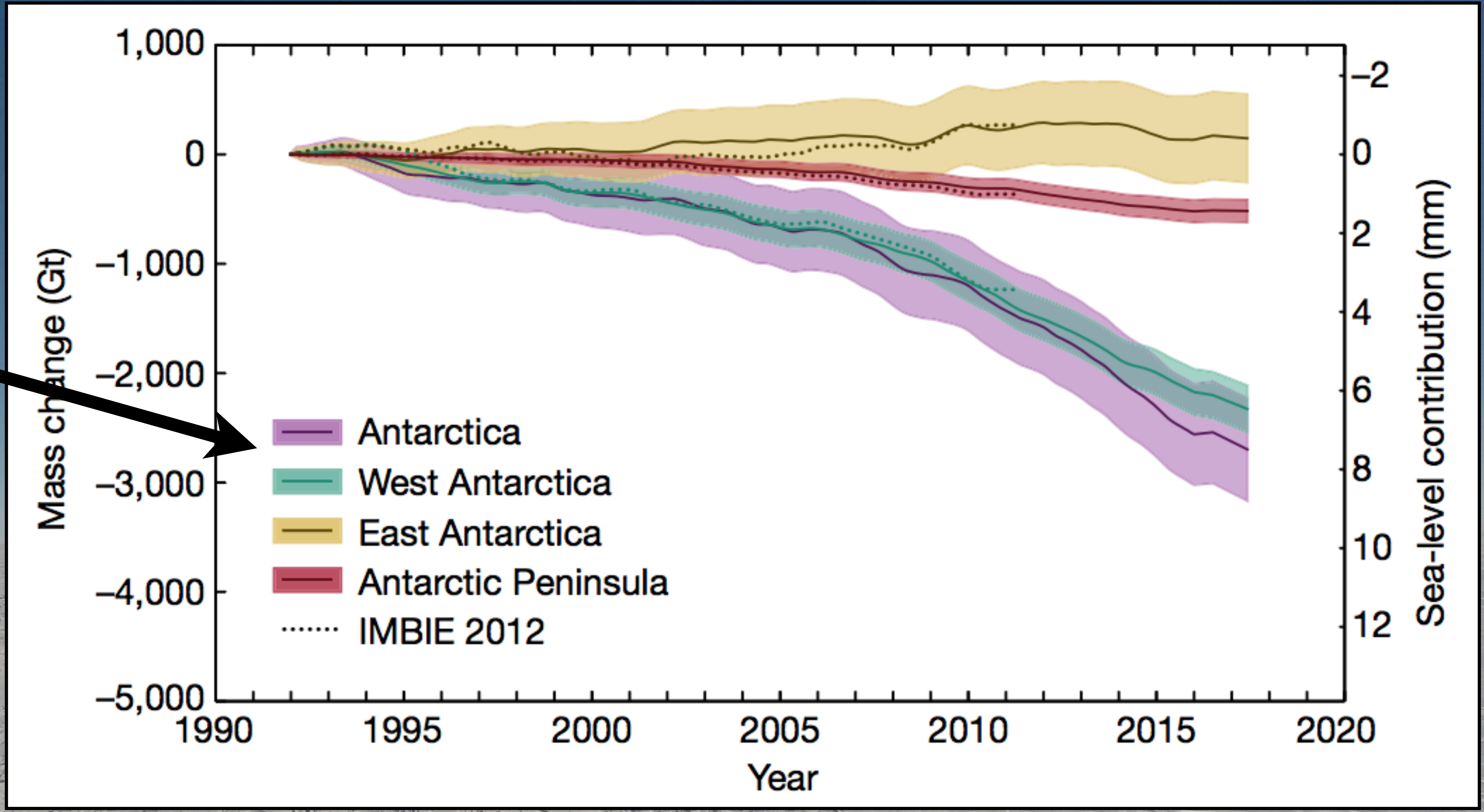
- Antarctica is rapidly losing mass into the ocean
  - Primary contribution from the West Antarctic Ice Sheet (WAIS)



Ice sheet mass change from lastest IMBIE estimate
Shepherd et al. 2018

Motivation

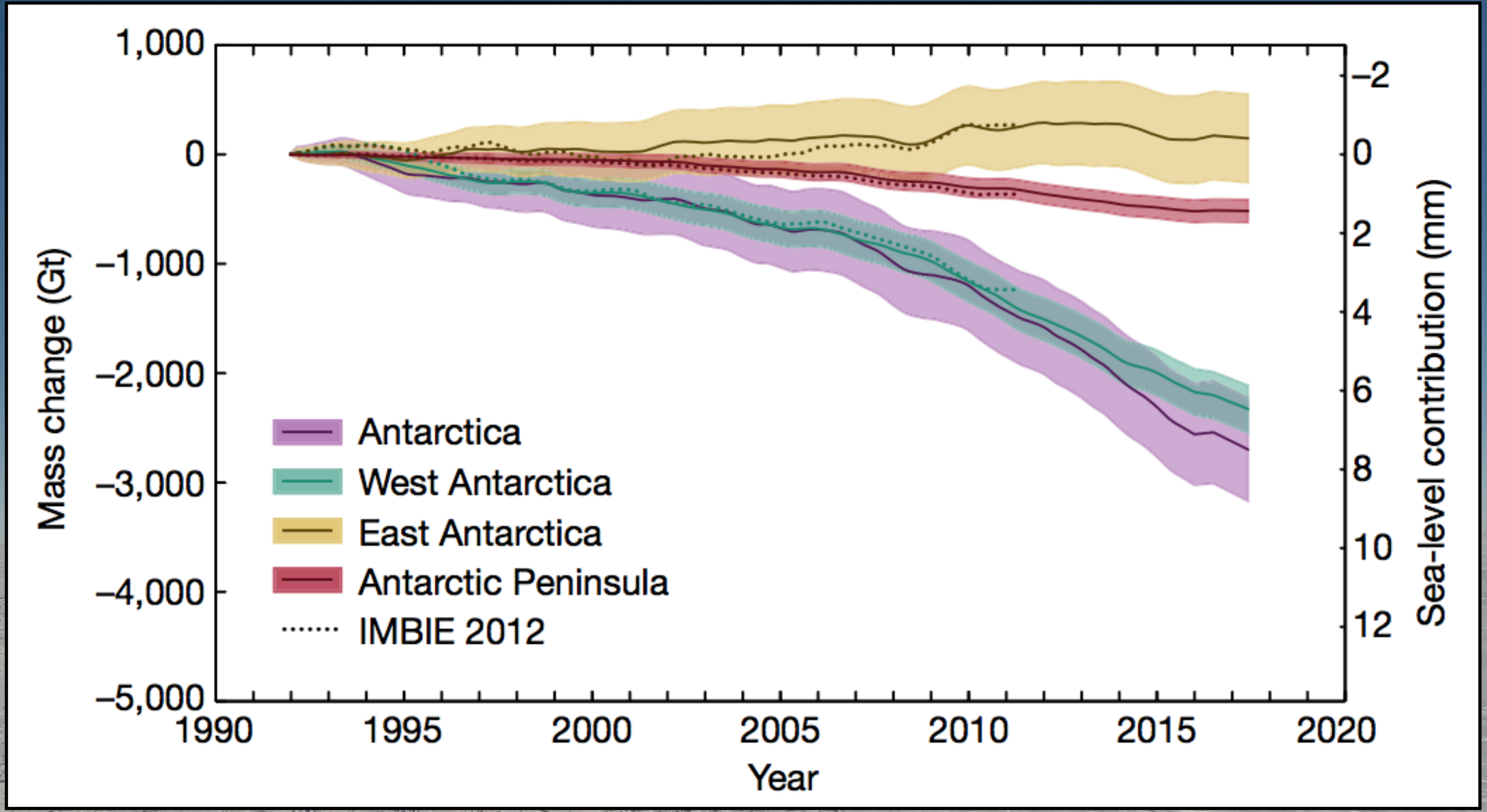
- **Antarctica is rapidly losing mass into the ocean**
  - **Primary contribution from the West Antarctic Ice Sheet (WAIS)**
  - **Rate of mass loss *tripled* in the last decade!**



Ice sheet mass change from lastest IMBIE estimate
Shepherd et al. 2018

Motivation

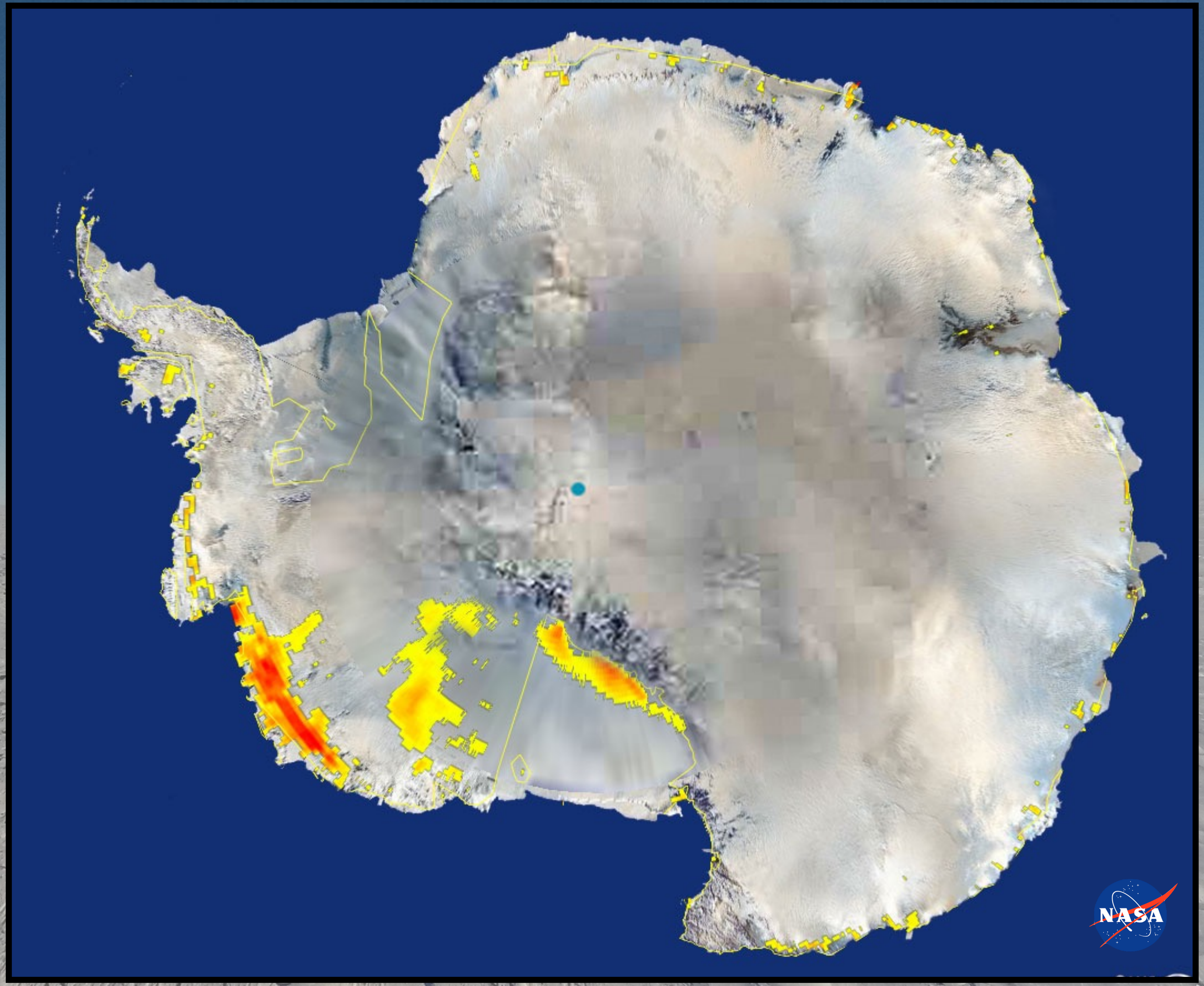
- Antarctica is rapidly losing mass into the ocean
  - Primary contribution from the West Antarctic Ice Sheet (WAIS)
  - Rate of mass loss *tripled* in the last decade!
  - Primarily driven by warm seawater thinning coastal ice shelves



Ice sheet mass change from lastest IMBIE estimate
Shepherd et al. 2018

Motivation

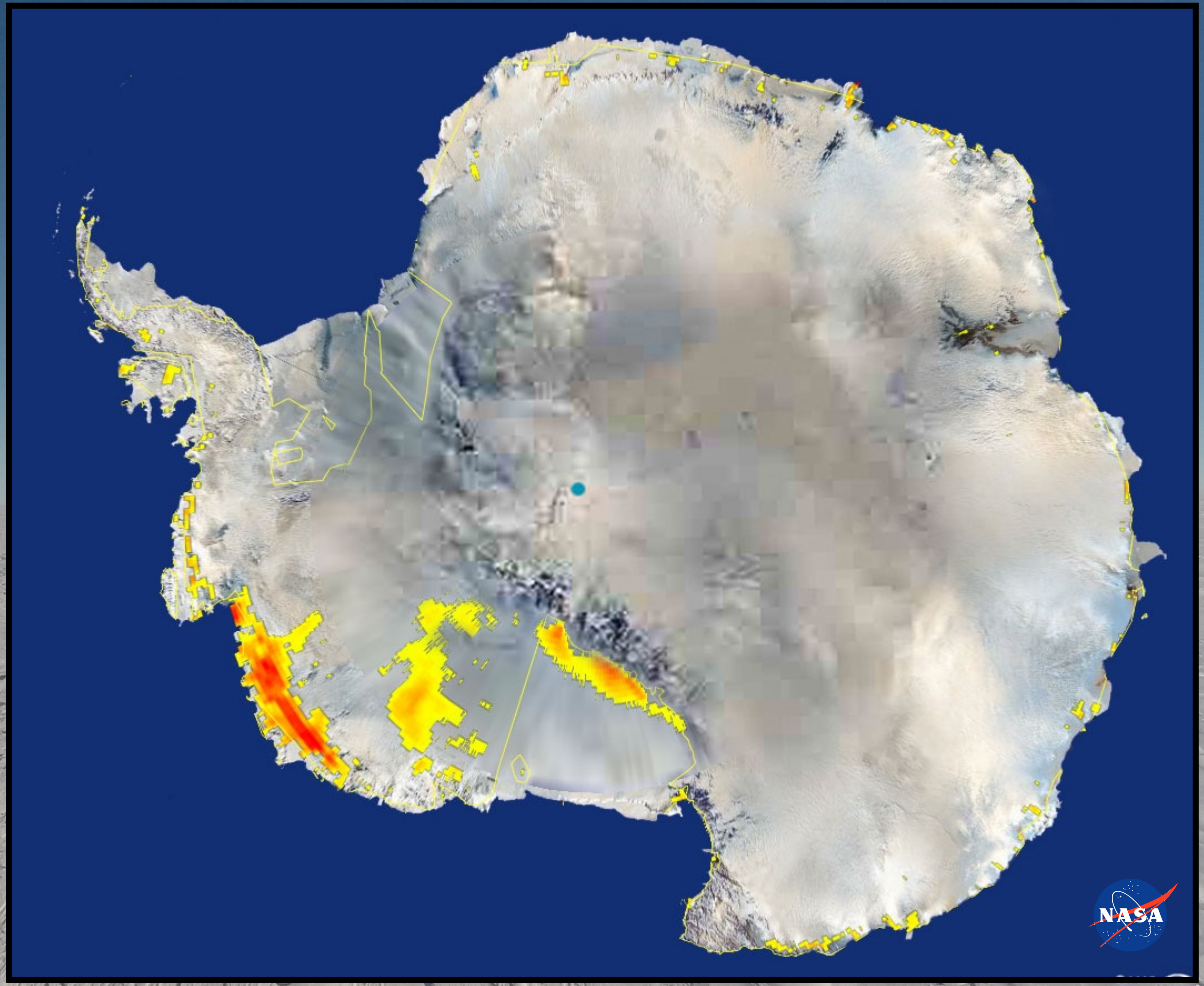
- Antarctica is rapidly losing mass into the ocean
  - Primary contribution from the West Antarctic Ice Sheet (WAIS)
  - Rate of mass loss *tripled* in the last decade!
  - Primarily driven by warm seawater thinning coastal ice shelves
  - Satellite microwave record also reveals extensive surface melt events



Refrozen melt layer observed by NASA's QuikSCAT scatterometer in January 2005

Motivation

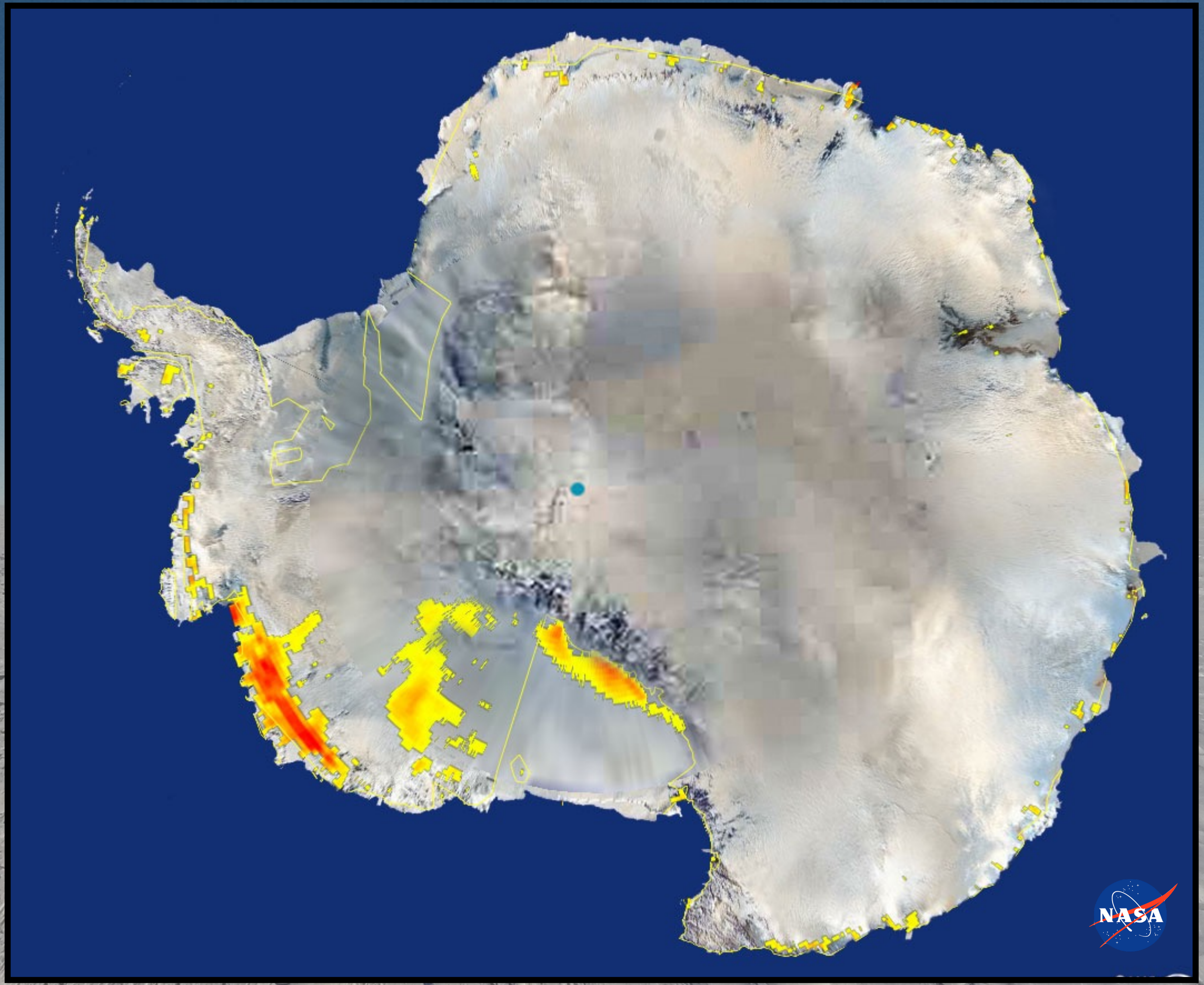
- Antarctica is rapidly losing mass into the ocean
  - Primary contribution from the West Antarctic Ice Sheet (WAIS)
  - Rate of mass loss *tripled* in the last decade!
  - Primarily driven by warm seawater thinning coastal ice shelves
  - Satellite microwave record also reveals extensive surface melt events
  - No significant atmospheric observations on the WAIS since the late 1960s
    - AWARE campaign in January 2016



Refrozen melt layer observed by NASA's QuikSCAT scatterometer in January 2005

Motivation

- Antarctica is rapidly losing mass into the ocean
  - Primary contribution from the West Antarctic Ice Sheet (WAIS)
  - Rate of mass loss *tripled* in the last decade!
  - Primarily driven by warm seawater thinning coastal ice shelves
  - Satellite microwave record also reveals extensive surface melt events
  - No significant atmospheric observations on the WAIS since the late 1960s
    - AWARE campaign in January 2016
  - Processes governing surface melt — from global to local scales — poorly understood



Refrozen melt layer observed by NASA's QuikSCAT scatterometer in January 2005

Objectives

<u>What are the Primary Physical Processes and Energy Fluxes Responsible for Driving Surface Melt on West Antarctica?</u>

Marine air advection
Cloud and radiative processes
Boundary layer dynamics
Sea ice cover, air-sea exchange

Objectives

What are the Primary Physical Processes and Energy Fluxes Responsible for Driving Surface Melt on West Antarctica?

Marine air advection
Cloud and radiative processes
Boundary layer dynamics
Sea ice cover, air-sea exchange

How is Surface Melting on West Antarctica Influenced by Tropical Pacific and High Latitude Climate Variability?

Southern Annular Mode (SAM)
Pacific-South American (PSA) Pattern
El Niño Southern Oscillation (ENSO)

Objectives

What are the Primary Physical Processes and Energy Fluxes Responsible for Driving Surface Melt on West Antarctica?

Marine air advection
Cloud and radiative processes
Boundary layer dynamics
Sea ice cover, air-sea exchange

How is Surface Melting on West Antarctica Influenced by Tropical Pacific and High Latitude Climate Variability?

Southern Annular Mode (SAM)
Pacific-South American (PSA) Pattern
El Niño Southern Oscillation (ENSO)

How Has the Summer Climate of West Antarctica Changed During the 21st Century?

Antarctic Peninsula Cooling (Turner et al. 2016)
Circumpolar Sea-Ice Expansion (Meehl et al. 2016)

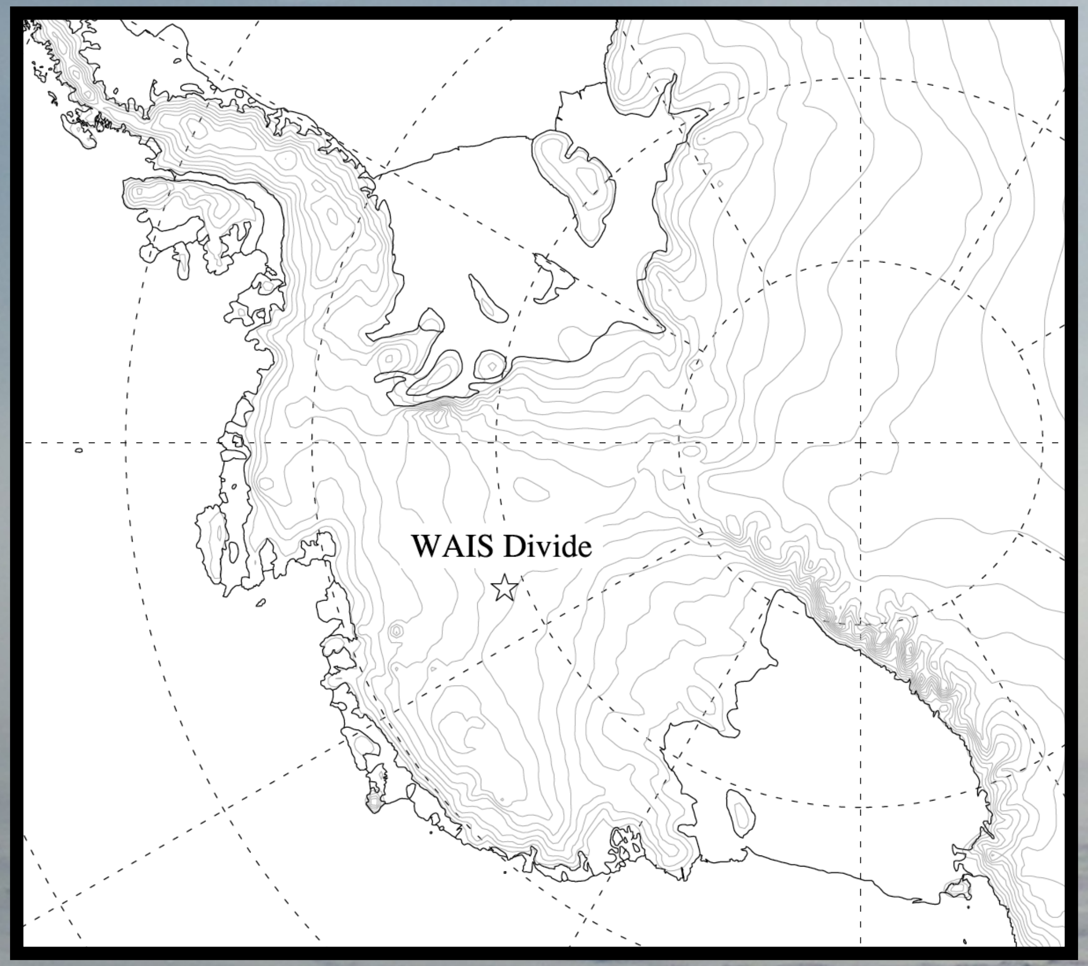
The ARM West Antarctic Radiation Experiment

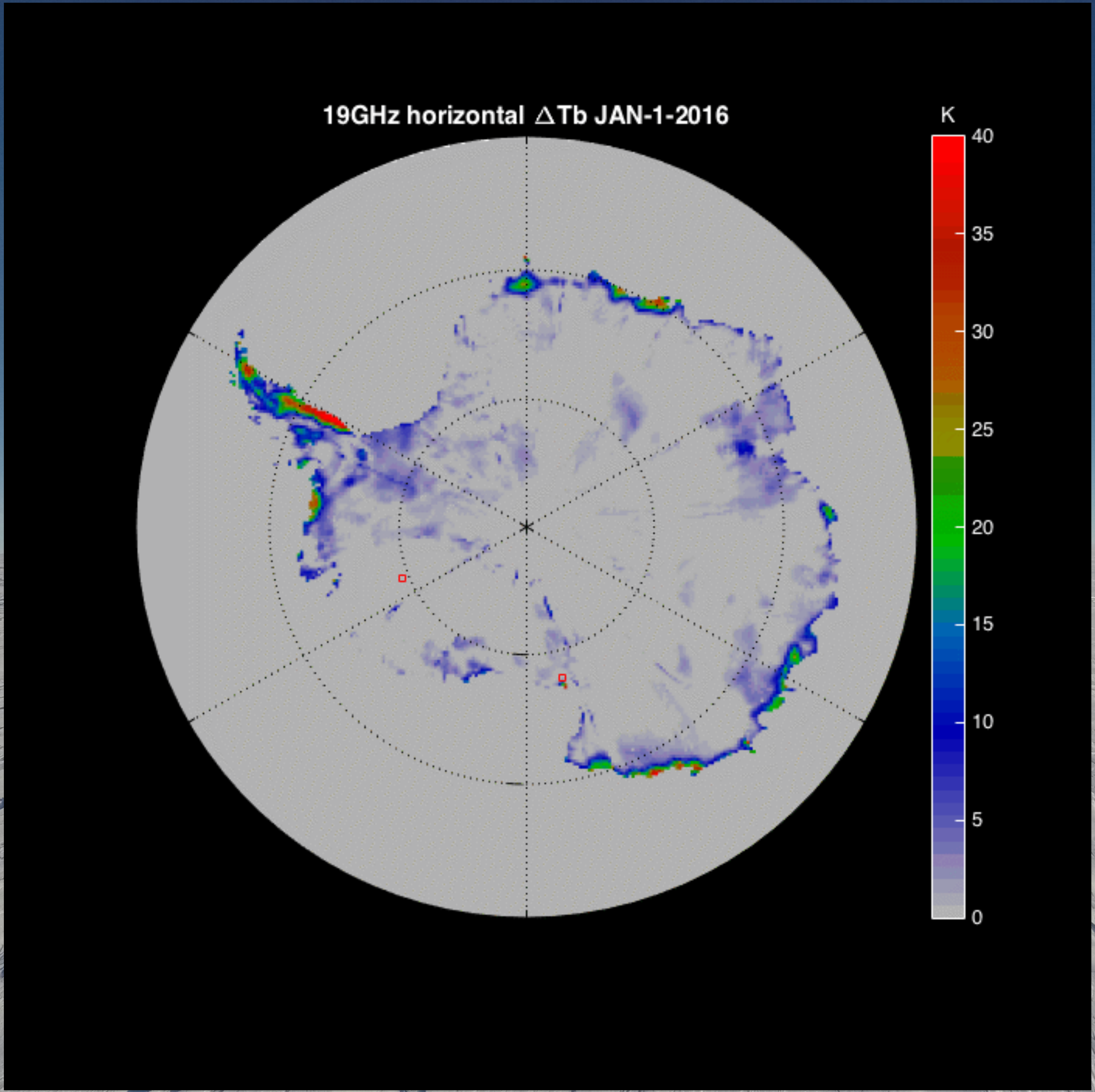
ARM "Extended Facility" deployed at WAIS Divide for 45 days in Dec 2015 - Jan 2016

The ARM West Antarctic Radiation Experiment

ARM "Extended Facility" deployed at
WAIS Divide for 45 days in Dec 2015 - Jan 2016

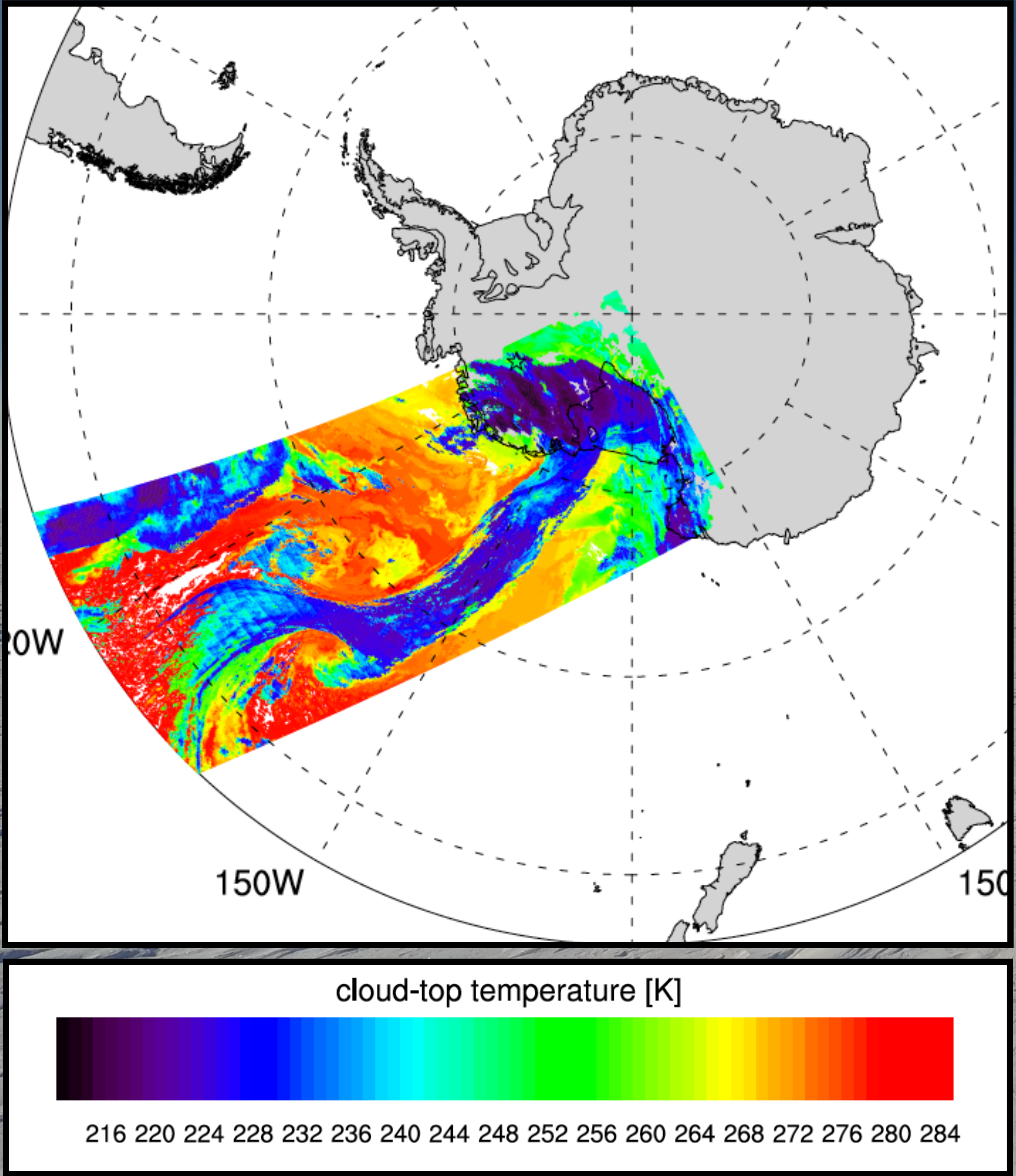
Captured first measurements in West Antarctica during a melt event



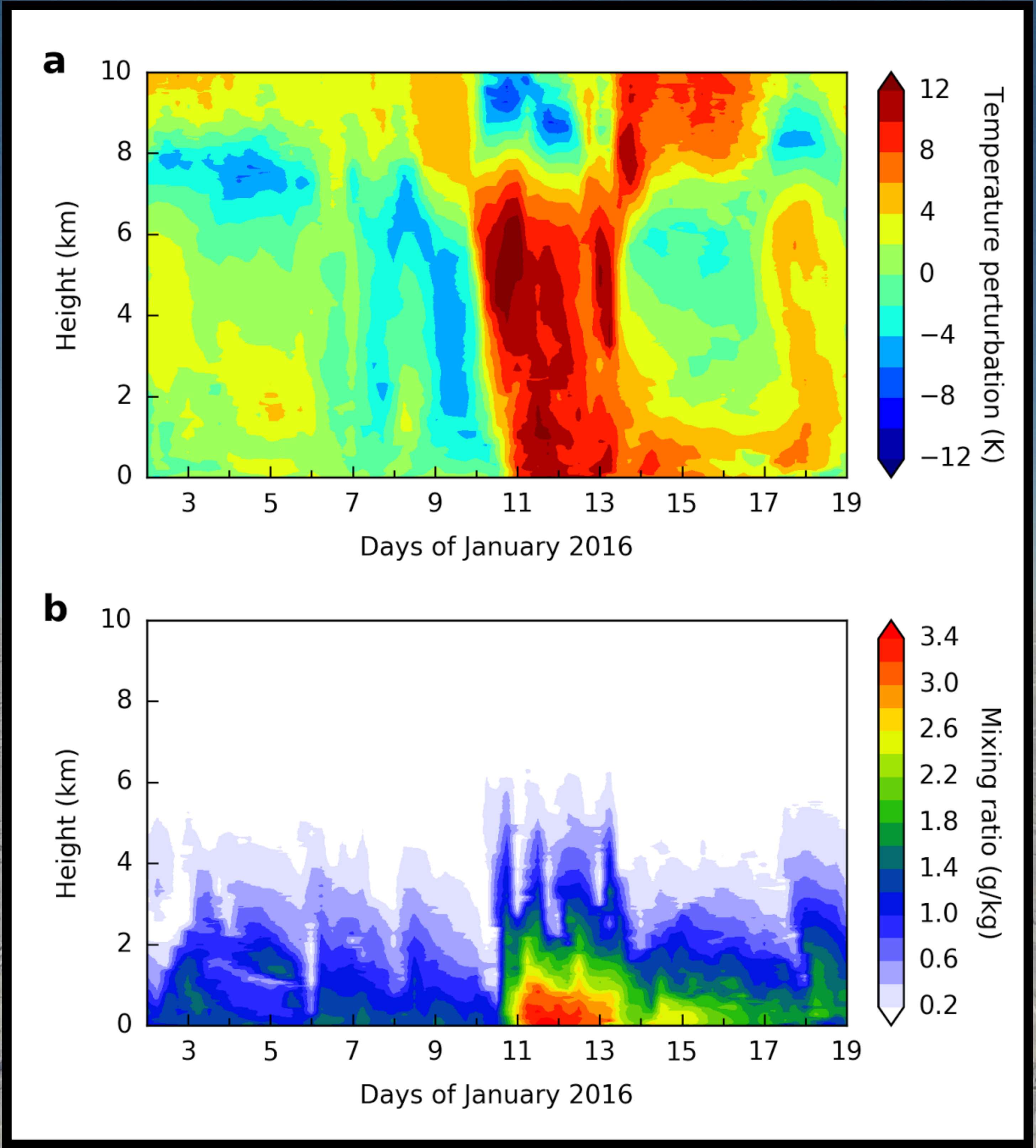

19GHz horizontal ΔTb JAN-1-2016
K
40
35
30
25
20
15
10
5
0

January 2016 Extensive Summer Melt in West Antarctica

Aqua MODIS Moisture Plume, 10 January

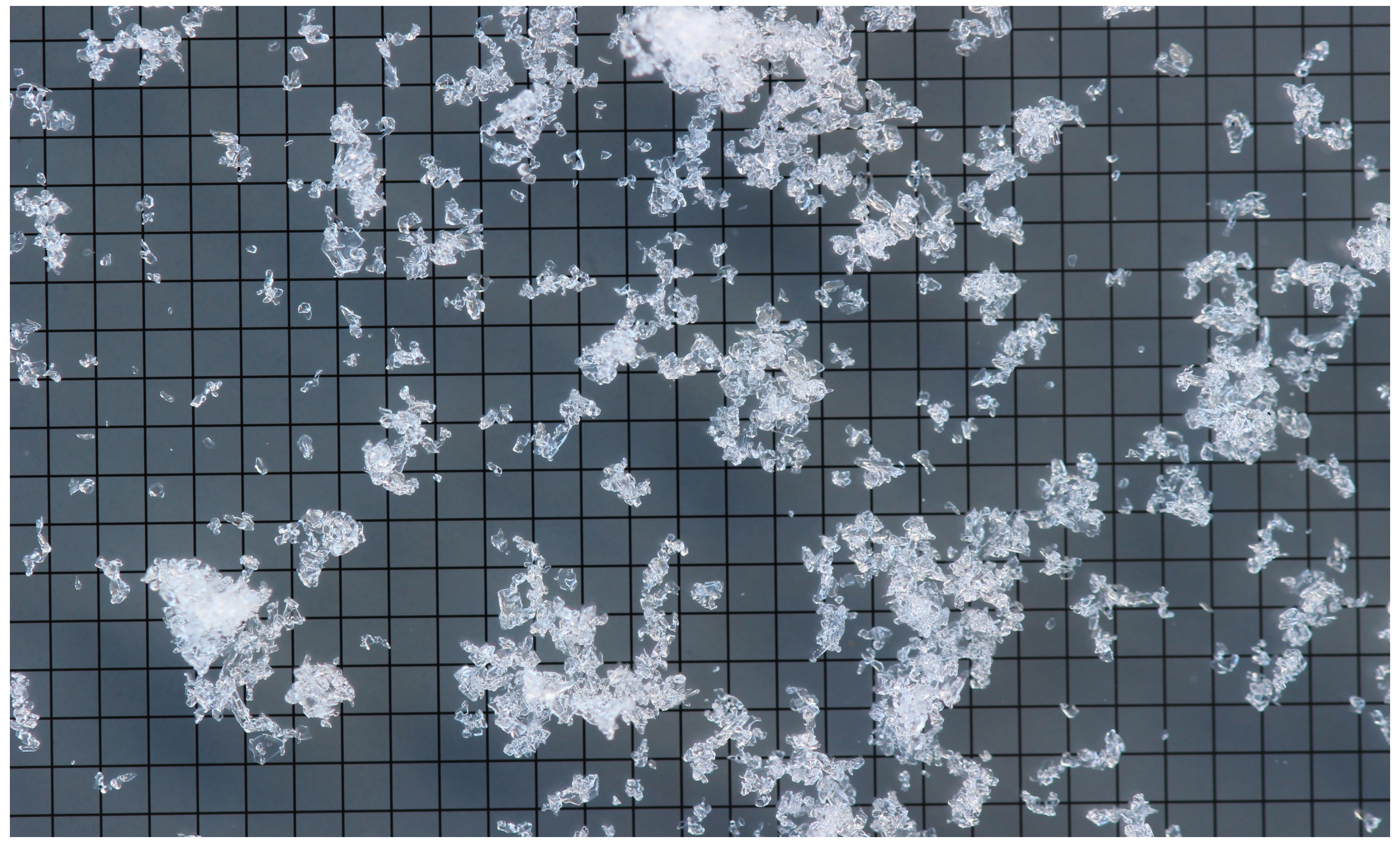


WAIS Divide Sondes

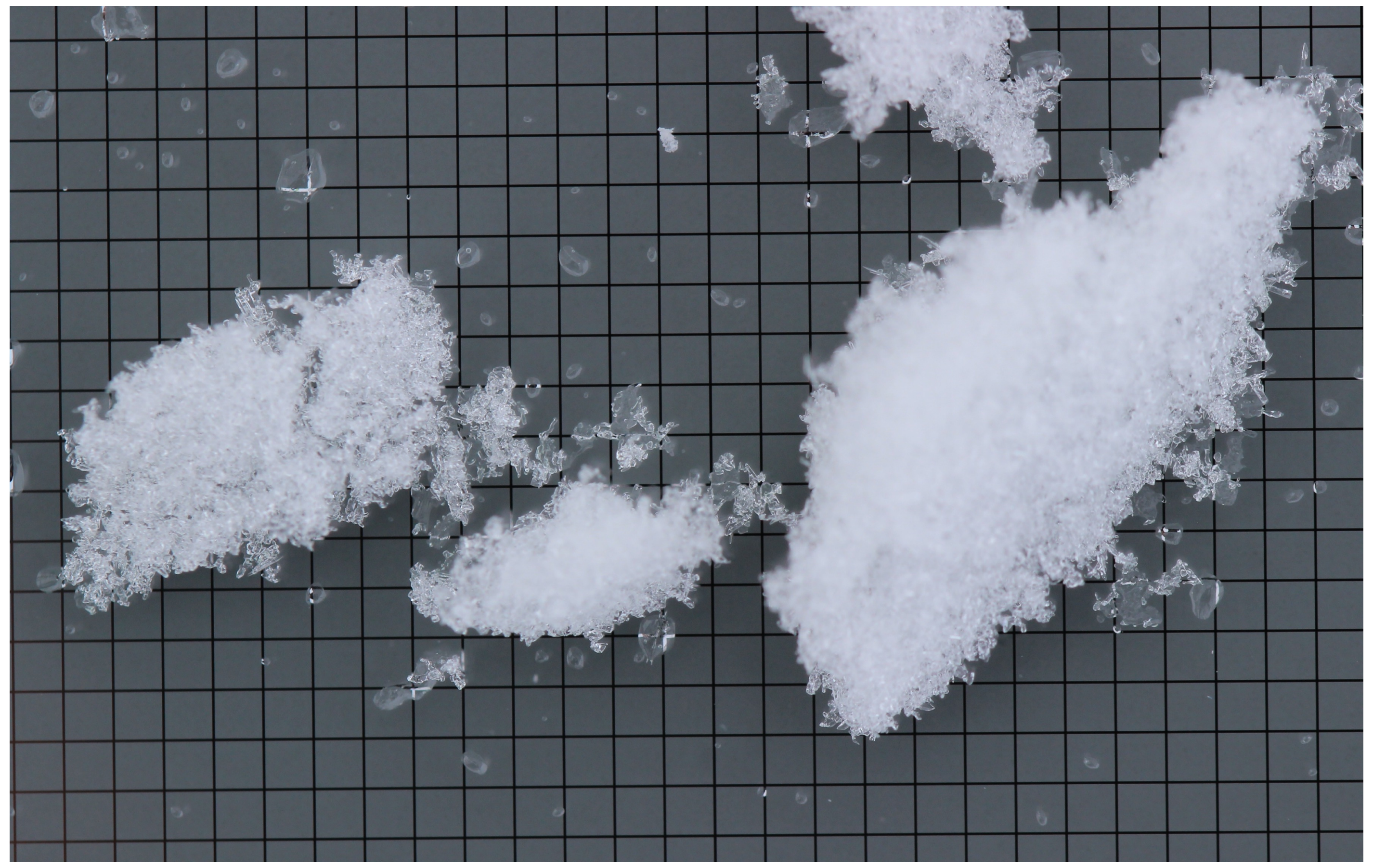


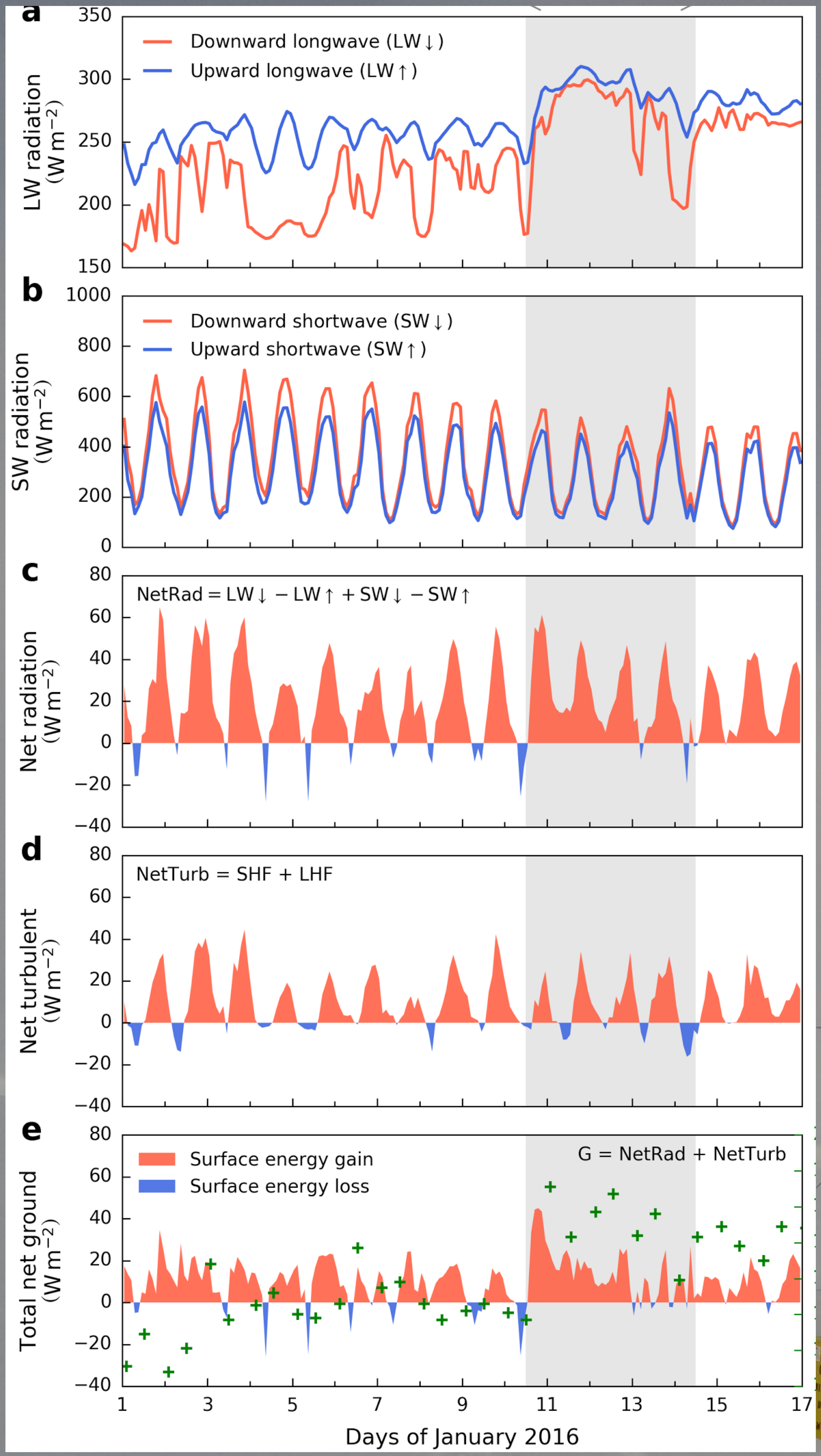
Snow Grain Photography

Before melt event, 8 Jan 2016



During melt event, 11 Jan 2016



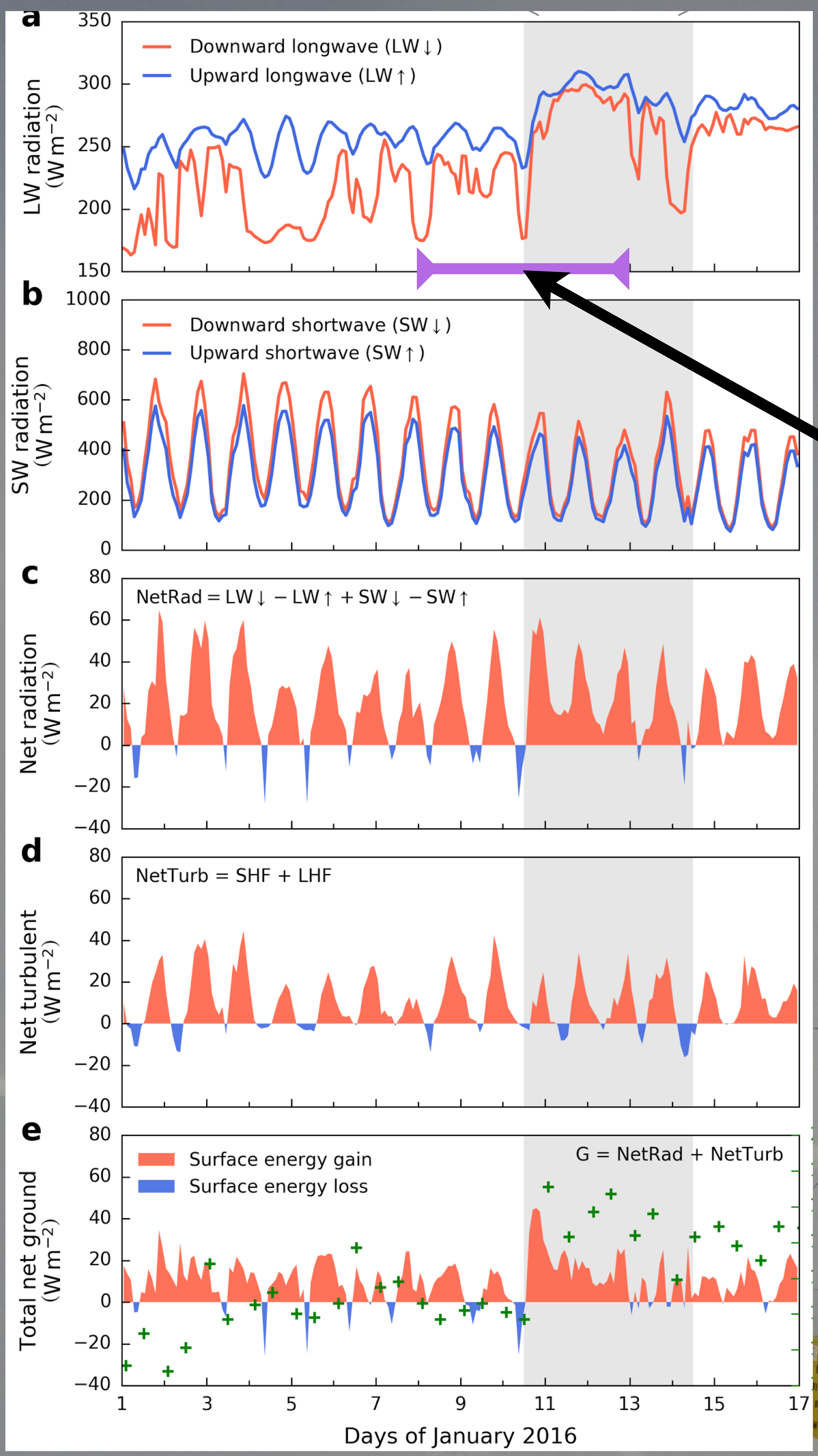


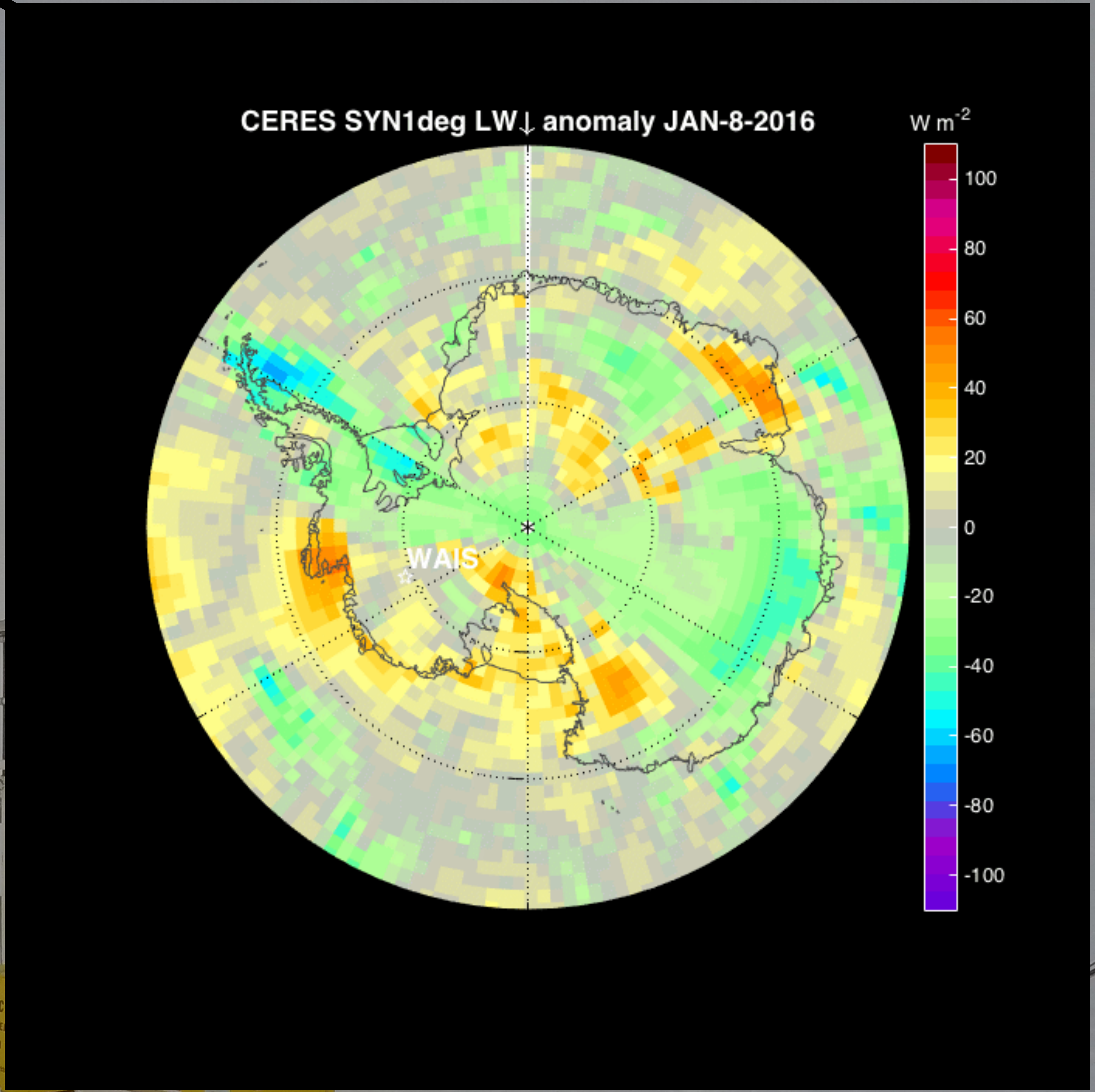
Snow Surface Energy Balance at WAIS Divide

- Ice-falling moisture plume drove large spike in downwelling LW radiation at the surface, of order 130 $W\ m^{-2}$

Snow Surface Energy Balance at WAIS Divide

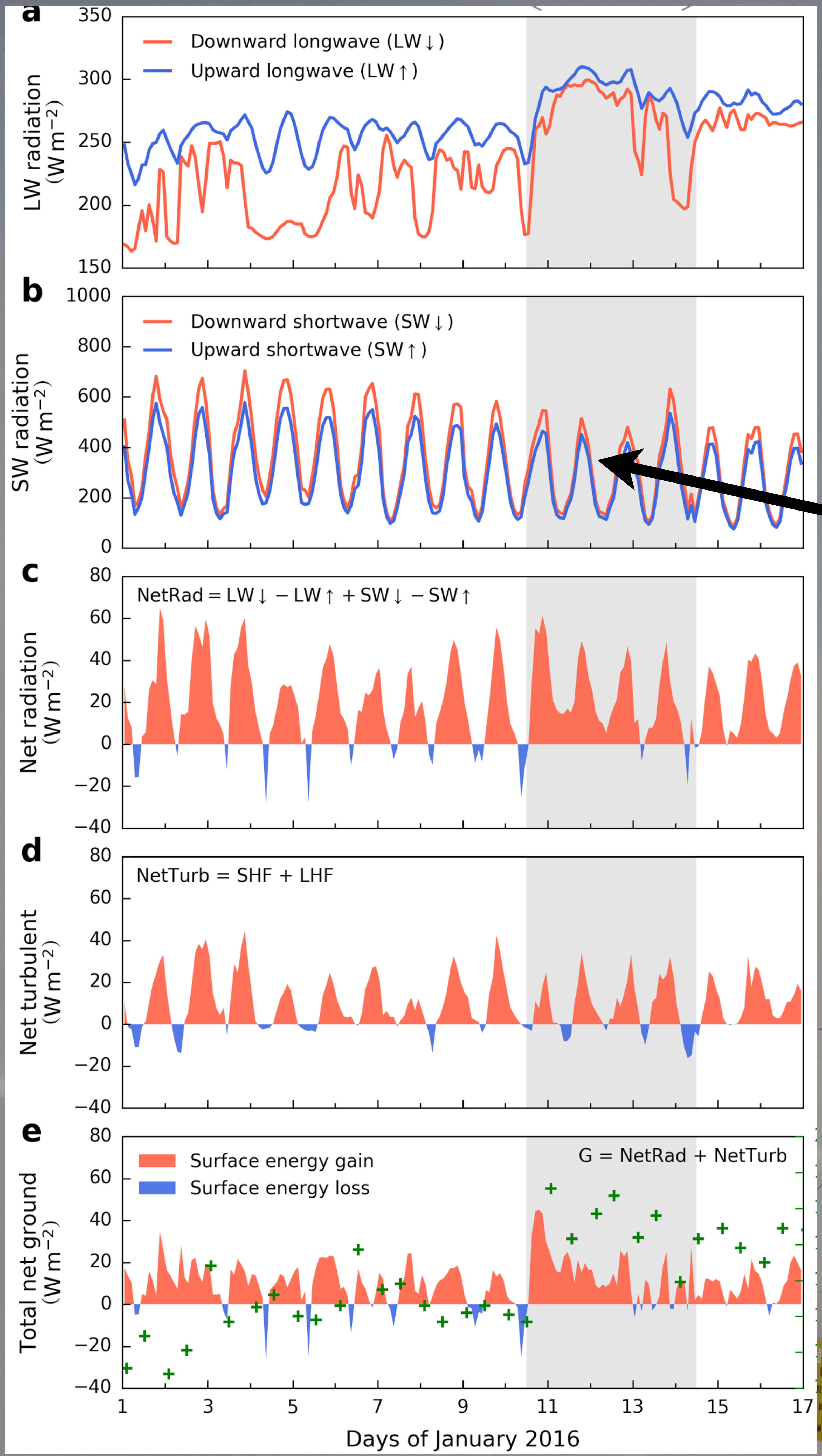
- Ice-falling moisture plume drove large spike in downwelling LW radiation at the surface, of order 130 $W\ m^{-2}$

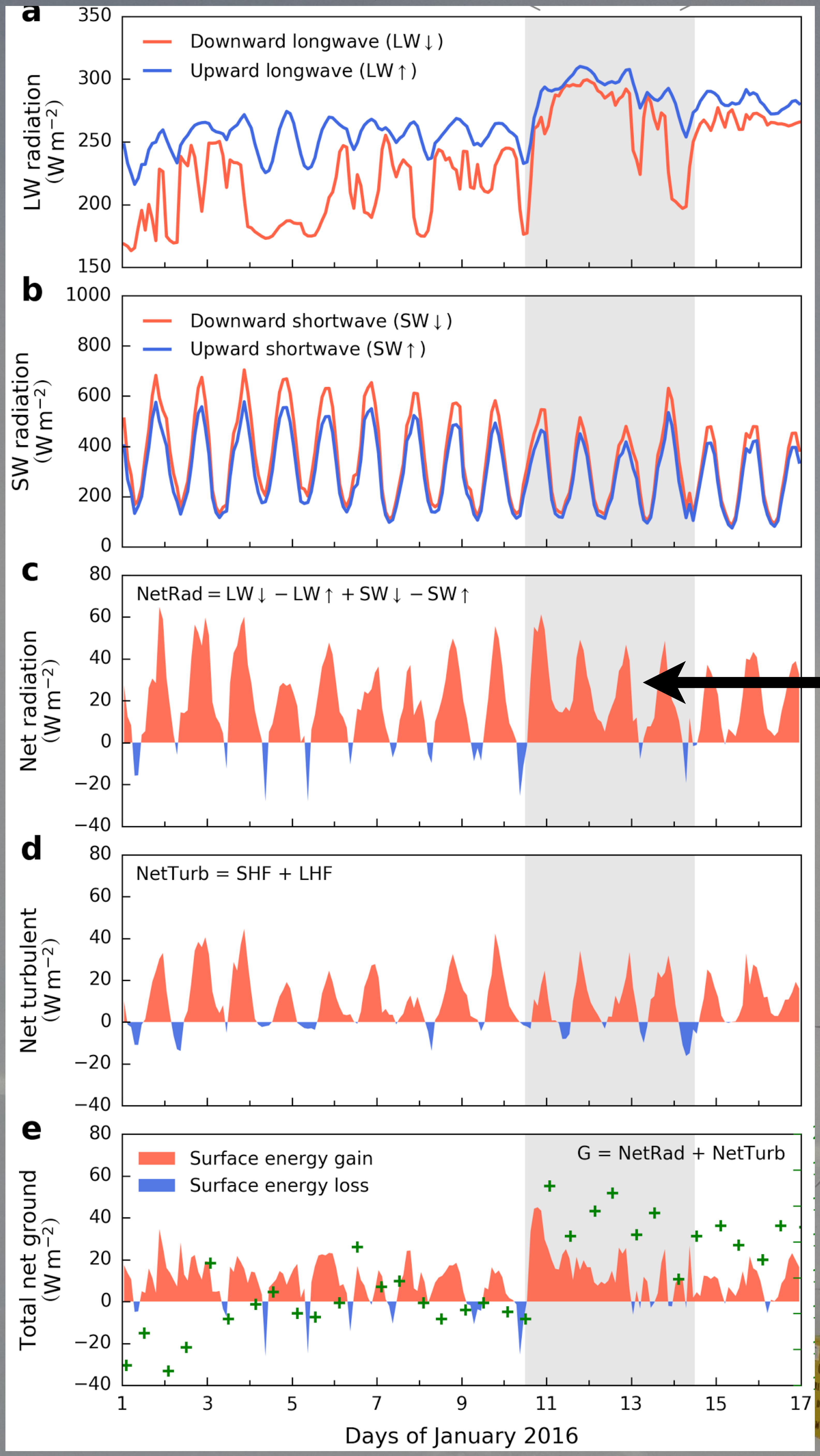




Snow Surface Energy Balance at WAIS Divide

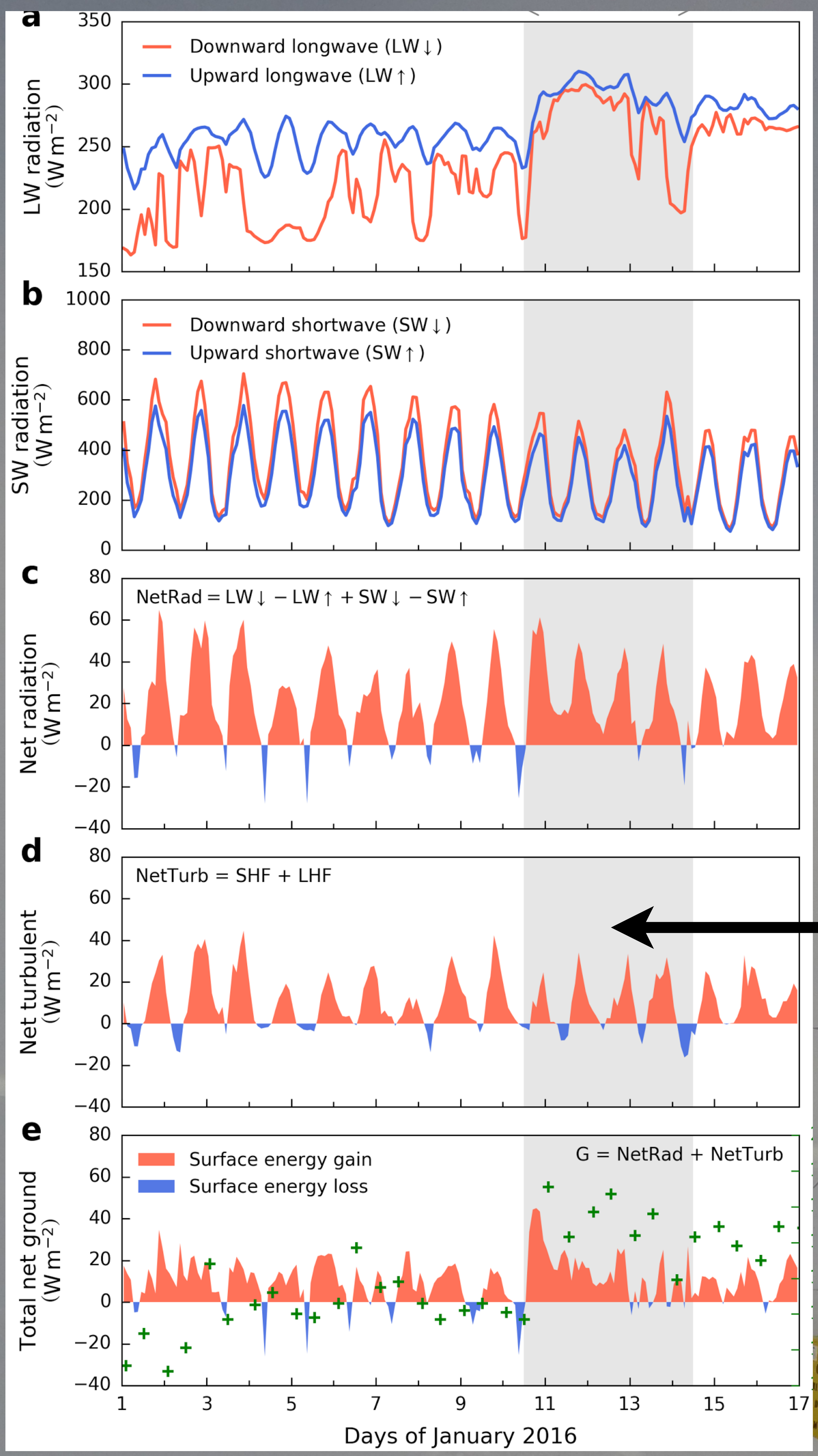
- Ice-falling moisture plume drove large spike in downwelling LW radiation at the surface, of order 130 $W\ m^{-2}$
- Small reduction in SW absorption relative to pre-event conditions





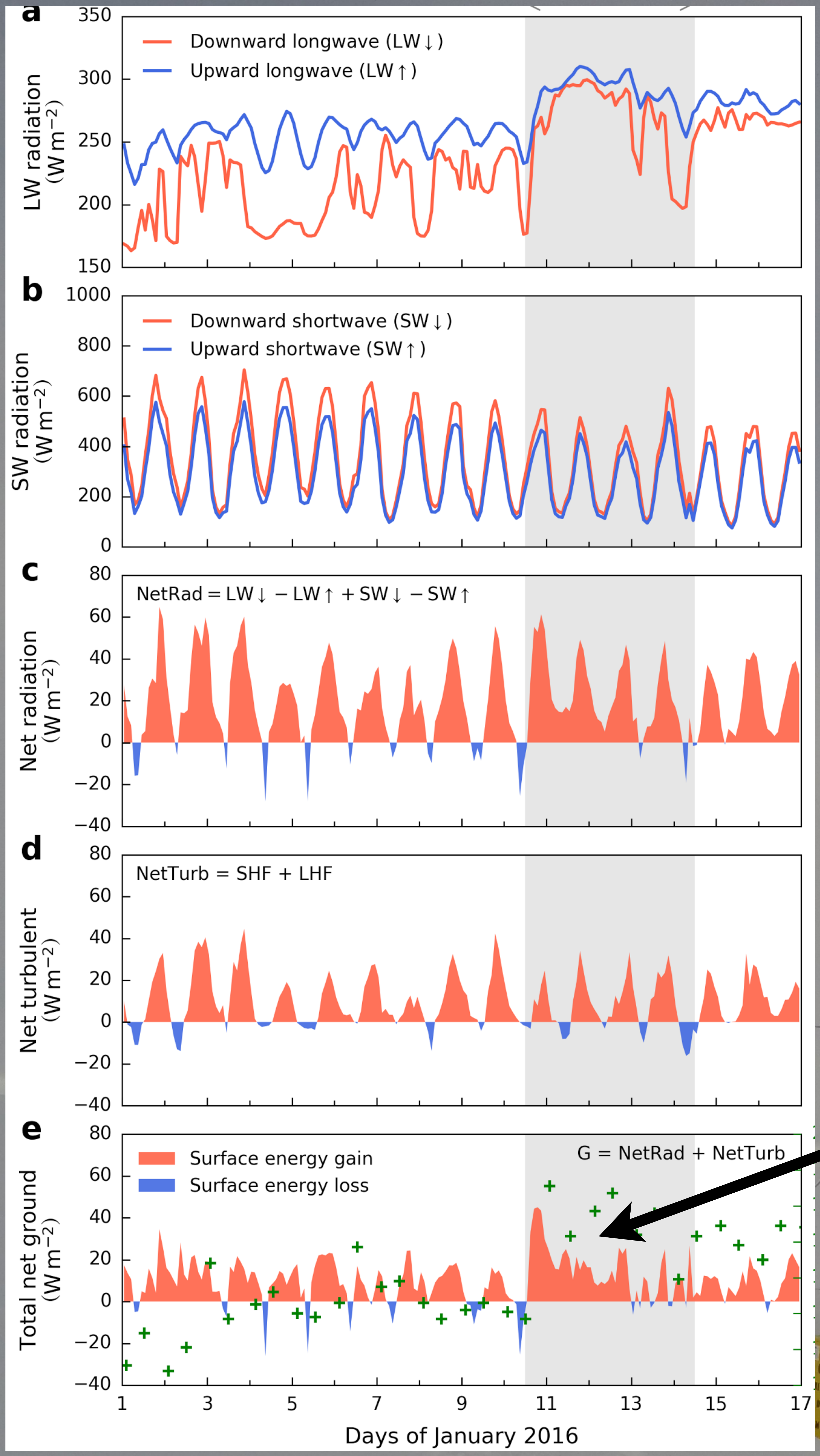
Snow Surface Energy Balance at WAIS Divide

- Ice-falling moisture plume drove large spike in downwelling LW radiation at the surface, of order 130 $W\ m^{-2}$
- Small reduction in SW absorption relative to pre-event conditions
- Net radiative heating of snowpack caused by atmospheric LW emission and absorption of incoming SW radiation



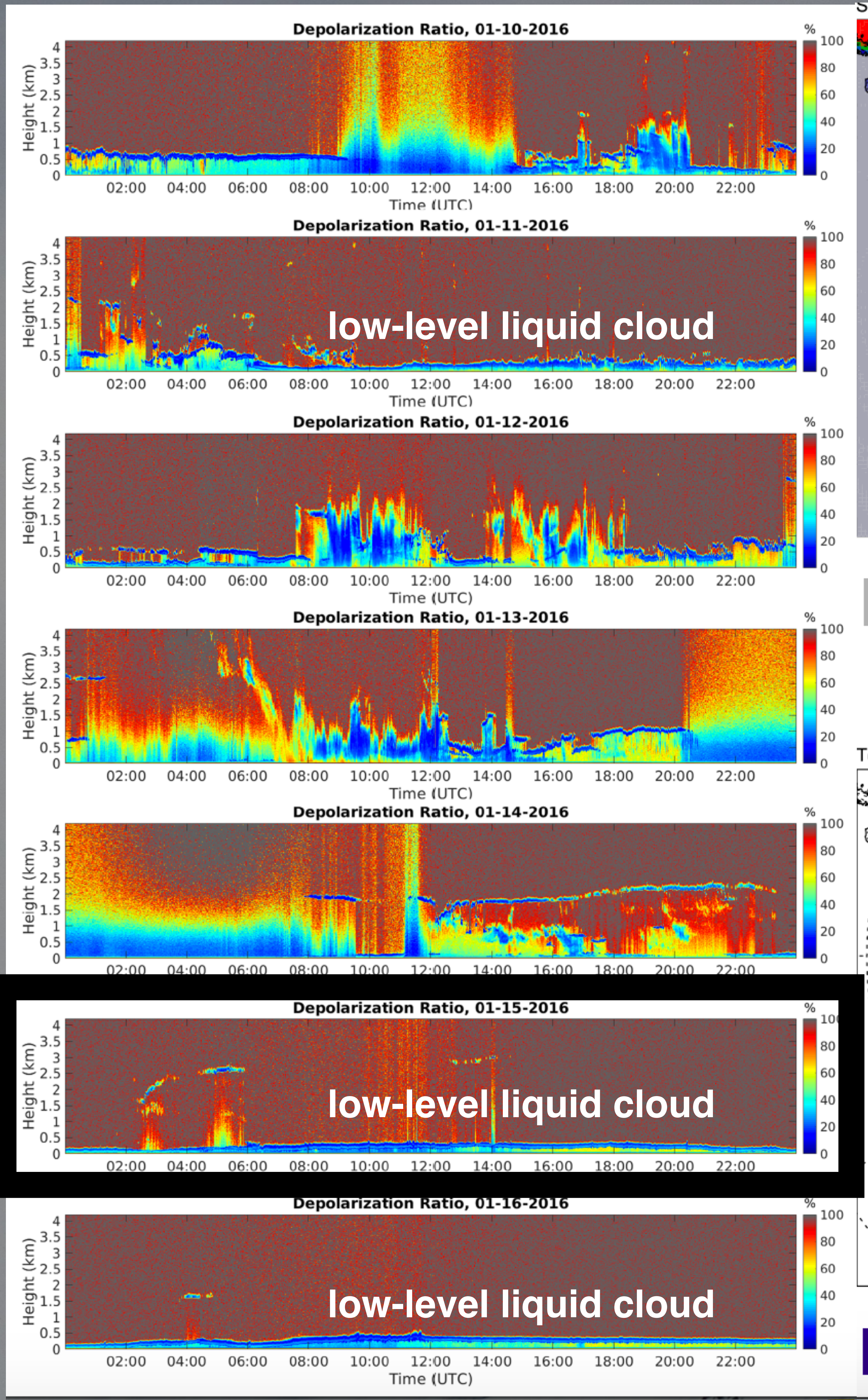
Snow Surface Energy Balance at WAIS Divide

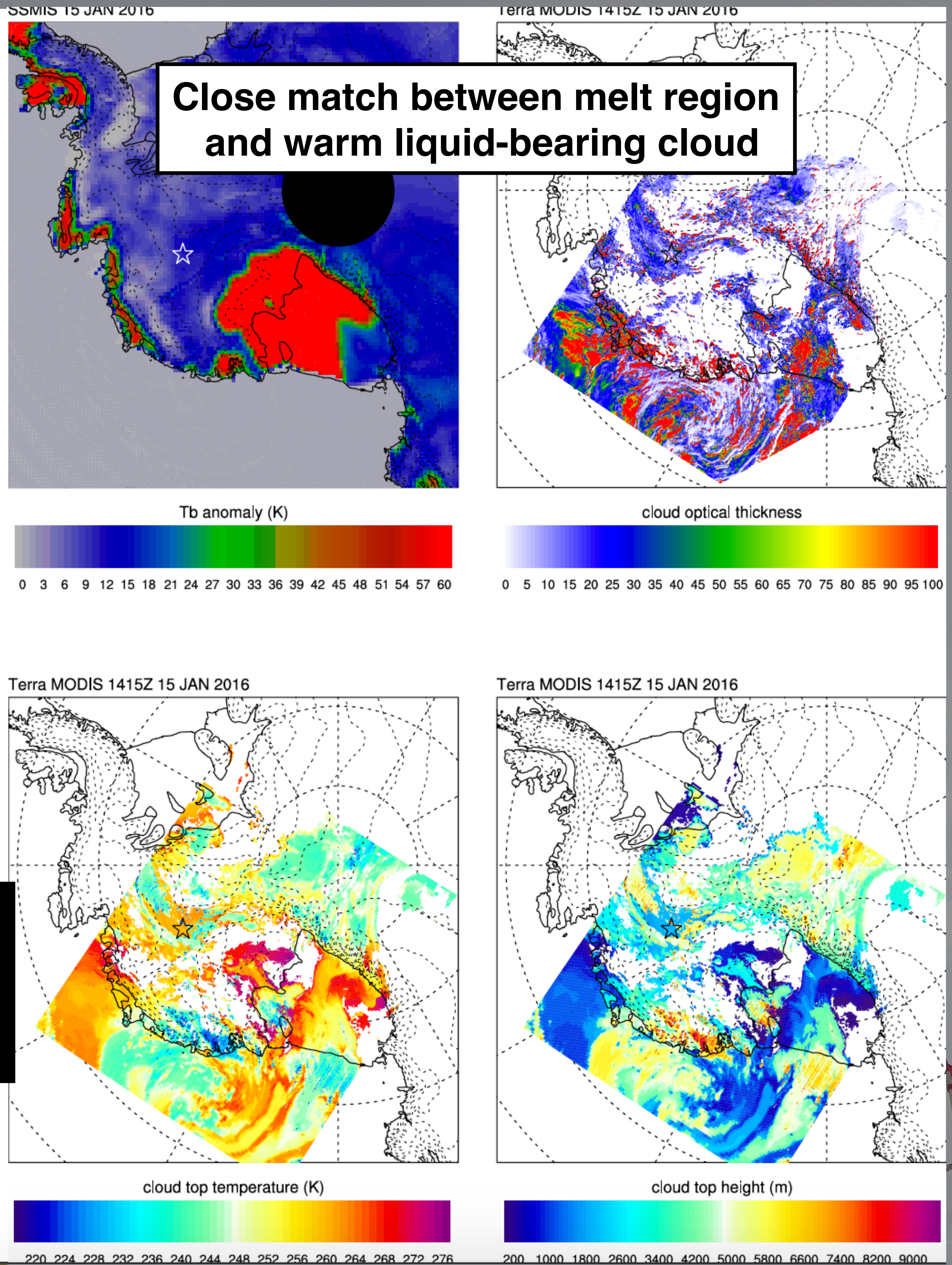
- Ice-falling moisture plume drove large spike in downwelling LW radiation at the surface, of order 130 $W\ m^{-2}$
- Small reduction in SW absorption relative to pre-event conditions
- Net radiative heating of snowpack caused by atmospheric LW emission and absorption of incoming SW radiation
- Net turbulent flux of sensible and latent heat largely unchanged relative to pre-event meteorological conditions



Snow Surface Energy Balance at WAIS Divide

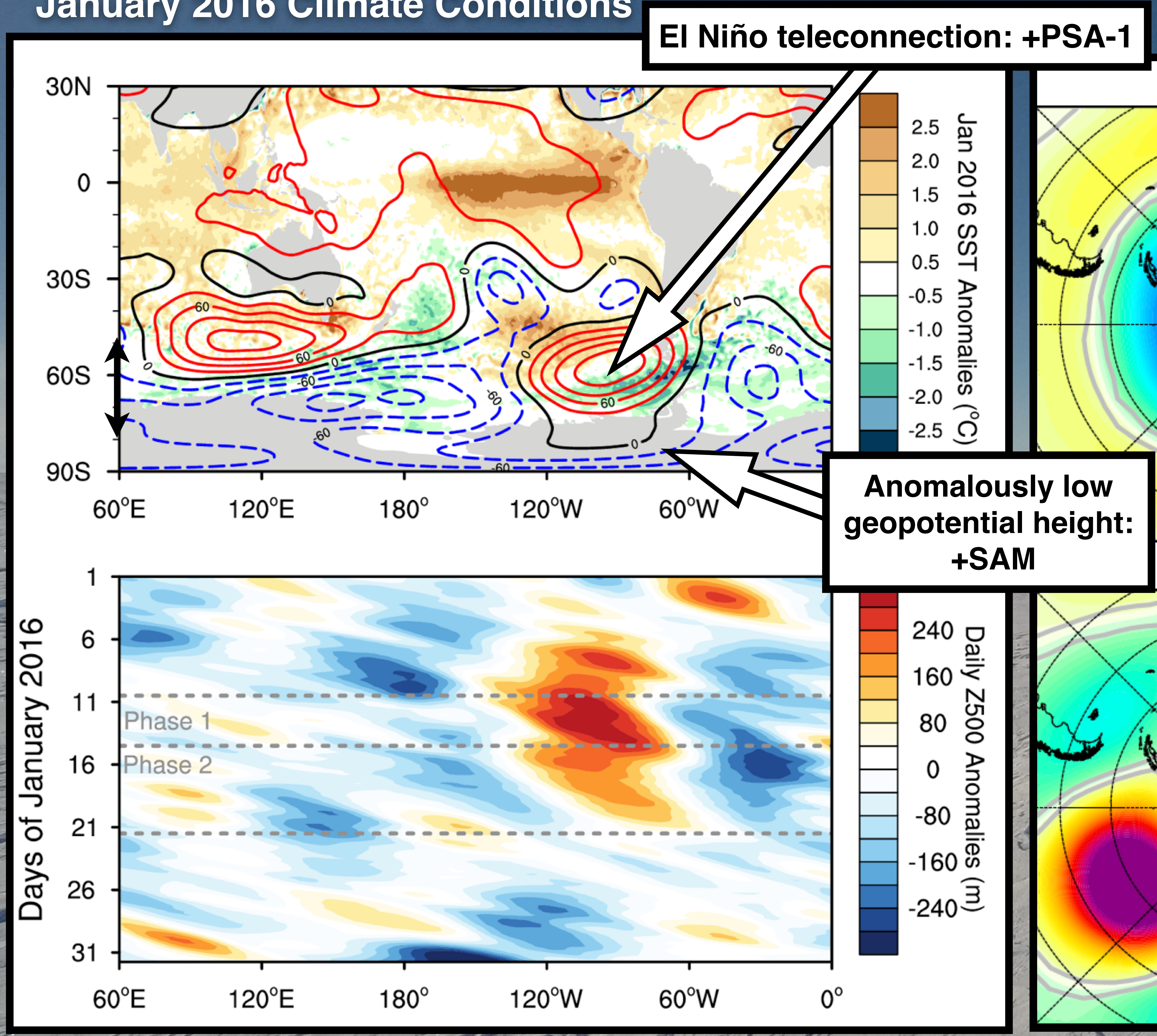
- Ice-falling moisture plume drove large spike in downwelling LW radiation at the surface, of order 130 $W\,m^{-2}$
- Small reduction in SW absorption relative to pre-event conditions
- Net radiative heating of snowpack caused by atmospheric LW emission and absorption of incoming SW radiation
- Net turbulent flux of sensible and latent heat largely unchanged relative to pre-event meteorological conditions
- Continuous surface energy gain


Depolarization Ratio, 01-10-2016
Depolarization Ratio, 01-11-2016
low-level liquid cloud
Depolarization Ratio, 01-12-2016
Depolarization Ratio, 01-13-2016
Depolarization Ratio, 01-14-2016
Depolarization Ratio, 01-15-2016
low-level liquid cloud
Depolarization Ratio, 01-16-2016
low-level liquid cloud
Height (km)
Time (UTC)
%

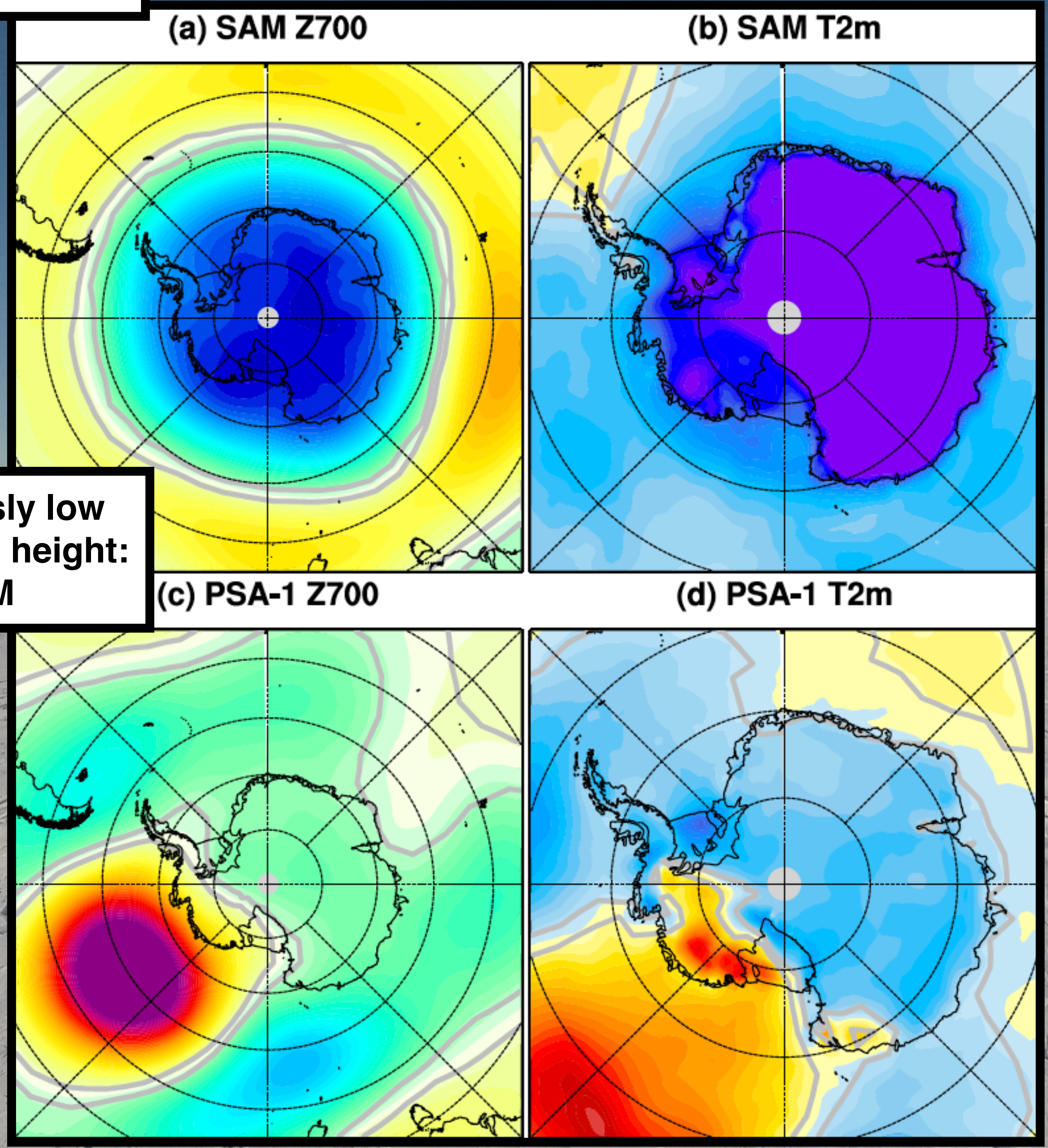

Close match between melt region and warm liquid-bearing cloud
SSMIS 15 JAN 2016
Tb anomaly (K)
Terra MODIS 1415Z 15 JAN 2016
cloud optical thickness
Terra MODIS 1415Z 15 JAN 2016
cloud top temperature (K)
Terra MODIS 1415Z 15 JAN 2016
cloud top height (m)

Large-Scale Forcing of the January 2016 Melt Event: Role of El Niño and +Southern Annular Mode

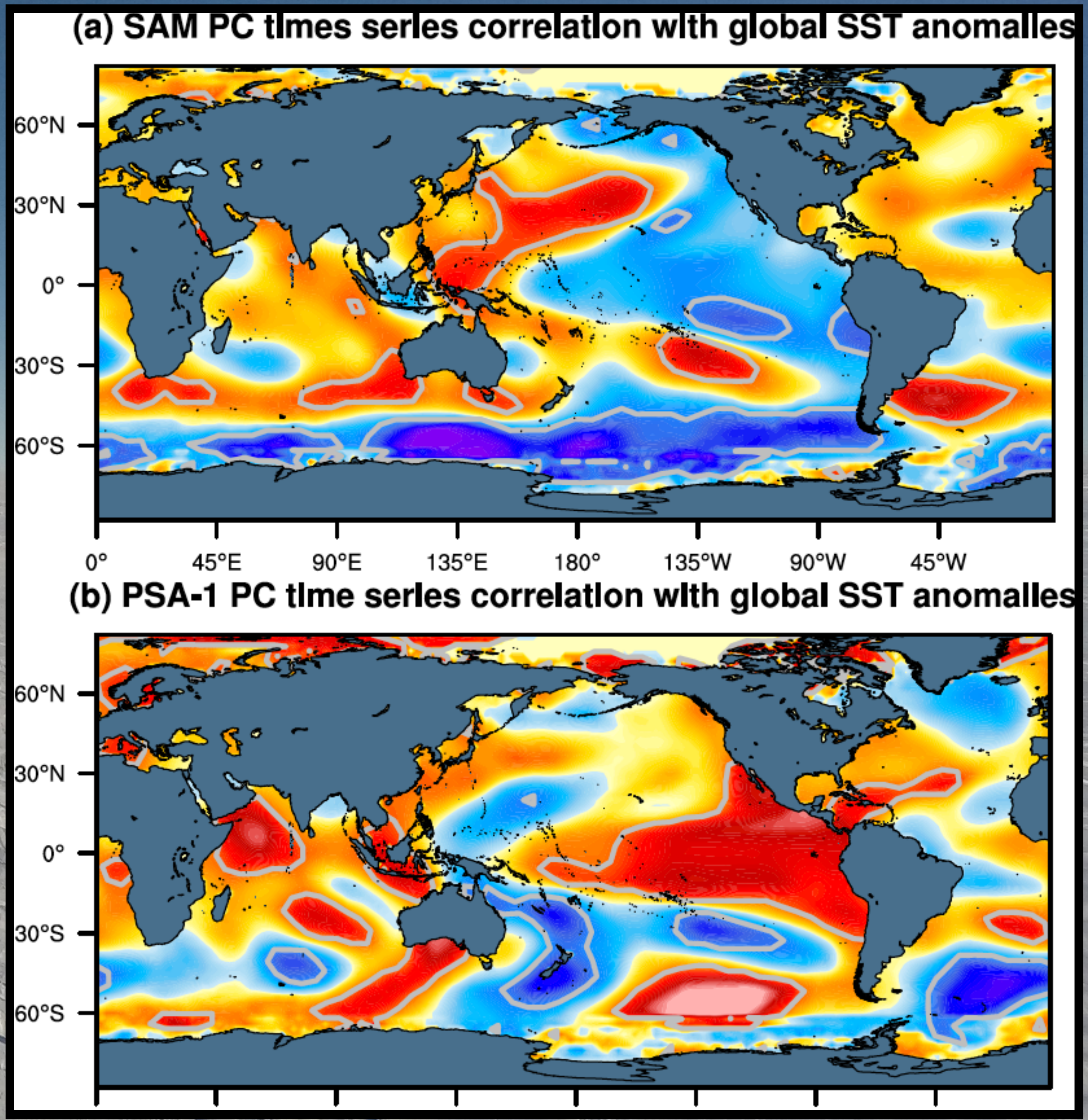
January 2016 Climate Conditions



Z700, T2m Regression on SAM, PSA-1



Historical Correlation with Global SST



+SAM normally favored by La Niña episodes / negative IPO; here, likely radiatively forced

January 2016 a rare event, mitigated by +SAM (opposing T2m response in Ross Embayment)

VOLUME 32 JOURNAL OF CLIMATE 1 FEBRUARY 2019

Meteorological Drivers and Large-Scale Climate Forcing of West Antarctic Surface Melt

RYAN C. SCOTT

Scripps Institution of Oceanography, La Jolla, California

JULIEN P. NICOLAS AND DAVID H. BROMWICH

Byrd Polar and Climate Research Center, The Ohio State University, Columbus, Ohio

JOEL R. NORRIS AND DAN LUBIN

Scripps Institution of Oceanography, La Jolla, California

(Manuscript received 19 April 2018, in final form 12 September 2018)

ABSTRACT

Understanding the drivers of surface melting in West Antarctica is crucial for understanding future ice loss and global sea level rise. This study identifies atmospheric drivers of surface melt on West Antarctic ice shelves and ice sheet margins and relationships with tropical Pacific and high-latitude climate forcing using multidecadal reanalysis and satellite datasets. Physical drivers of ice melt are diagnosed by comparing satellite-observed melt patterns to anomalies of reanalysis near-surface air temperature, winds, and satellite-derived cloud cover, radiative fluxes, and sea ice concentration based on an Antarctic summer synoptic climatology spanning 1979–2017. Summer warming in West Antarctica is favored by Amundsen Sea (AS) blocking activity and a negative phase of the southern annular mode (SAM), which both correlate with El Niño conditions in the tropical Pacific Ocean. Extensive melt events on the Ross–Amundsen sector of the West Antarctic Ice Sheet (WAIS) are linked to persistent, intense AS blocking anticyclones, which force intrusions of marine air over the ice sheet. Surface melting is primarily driven by enhanced downwelling longwave radiation from clouds and a warm, moist atmosphere and by turbulent mixing of sensible heat to the surface by föhn winds. Since the late 1990s, concurrent with ocean-driven WAIS mass loss, summer surface melt occurrence has increased from the Amundsen Sea Embayment to the eastern Ross Ice Shelf. We link this change to increasing anticyclonic advection of marine air into West Antarctica, amplified by increasing air–sea fluxes associated with declining sea ice concentration in the coastal Ross–Amundsen Seas.

Antarctic Melt Season Synoptic Climatology

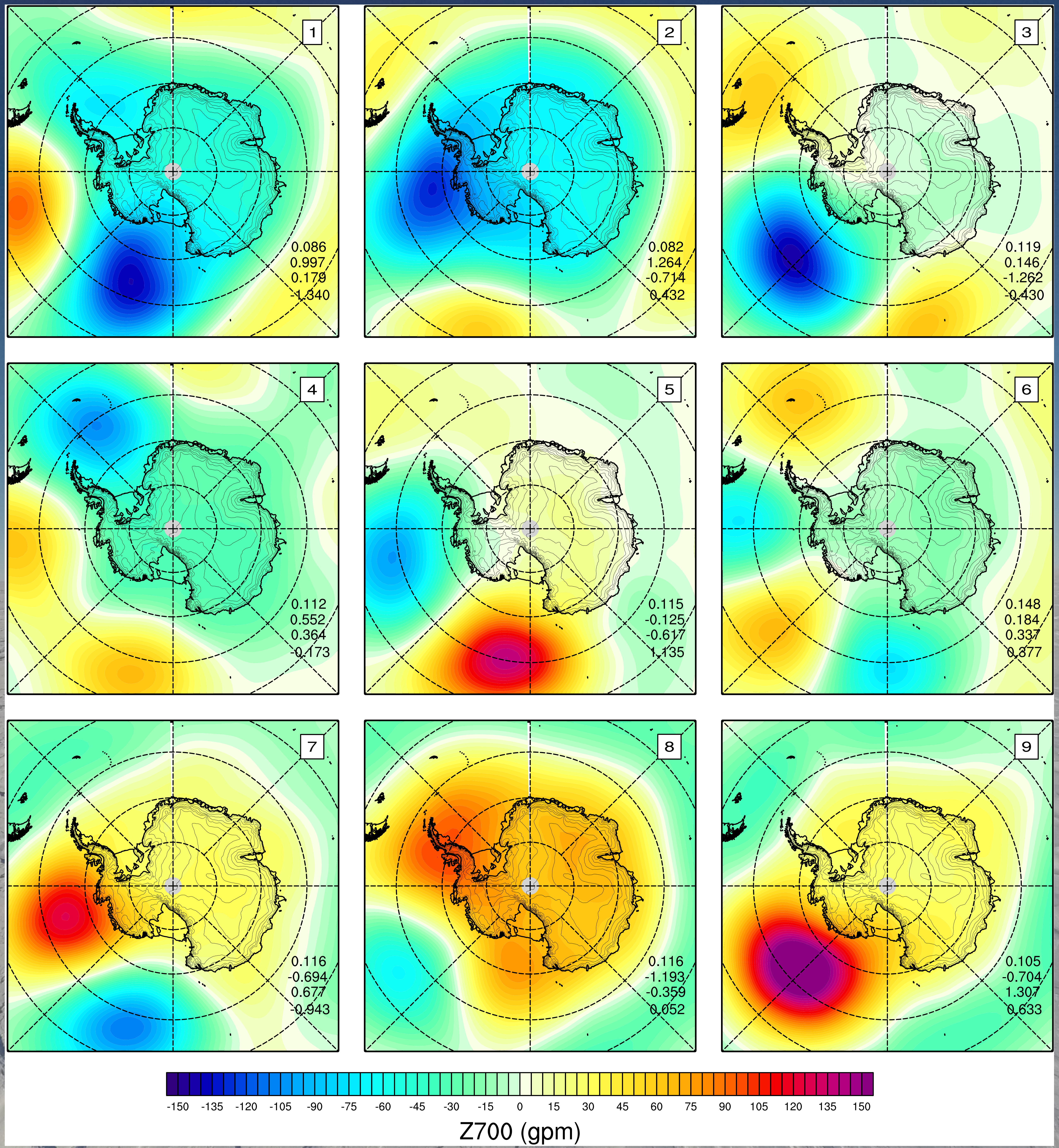
- EOF and *k*-means cluster analysis of daily lower tropospheric circulation (700-mb geopotential height anomalies)

Dec - Jan 1979-2017

- \+ SAM patterns: 1 - 4, 6
  \- SAM patterns: 5, 7 - 9

- Patterns 2 - 4 associated with La Niña +SAM and deep Amundsen Sea Low

- Patterns 8 - 9 associated with El Niño -SAM and Amundsen Sea high-pressure



Antarctic Melt Season Synoptic Climatology

- EOF and *k*-means cluster analysis of daily lower tropospheric circulation (700-mb geopotential height anomalies)

Dec - Jan 1979-2017

- + SAM patterns: 1 - 4, 6
  - SAM patterns: 5, 7 - 9

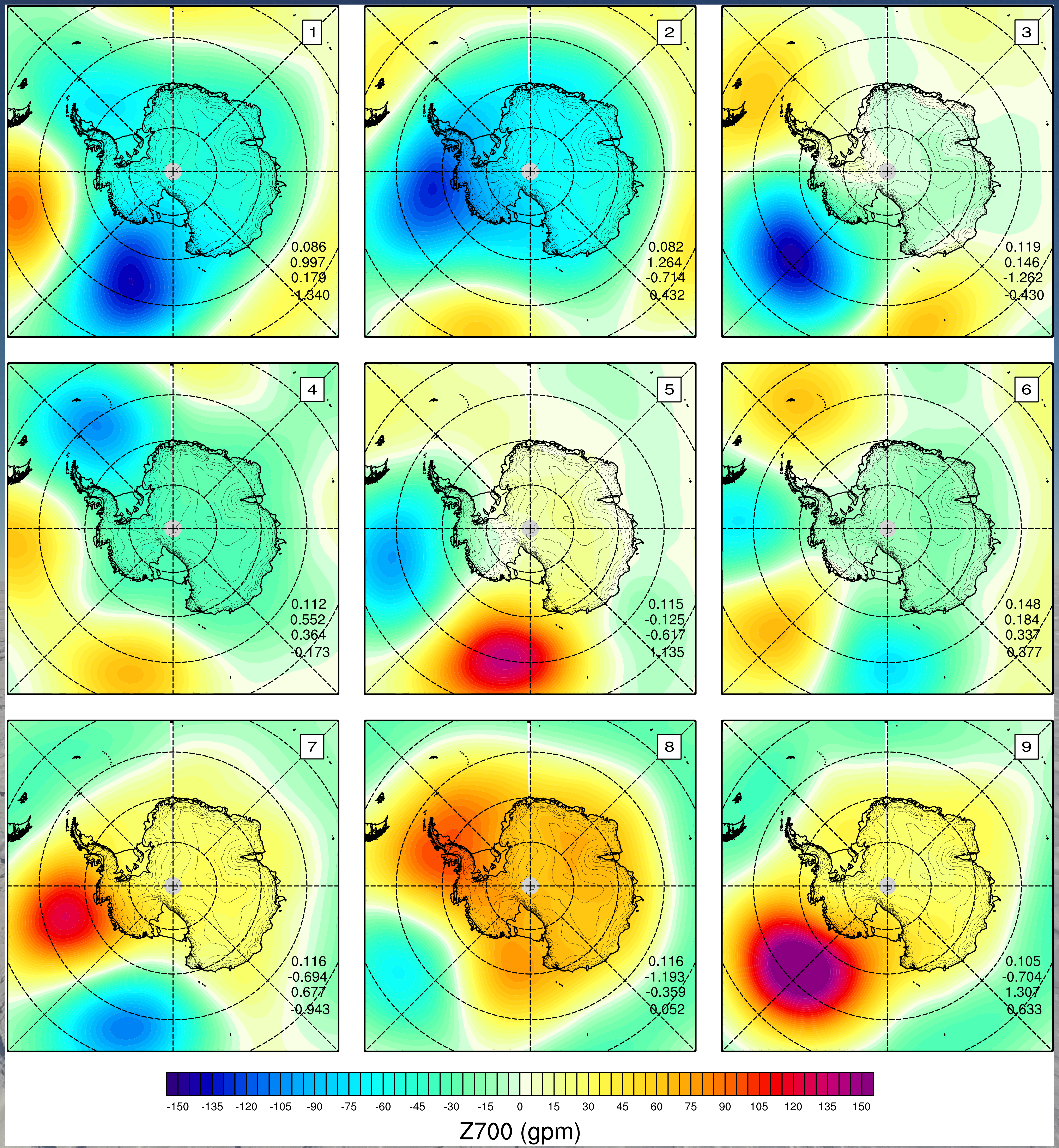
- Patterns 2 - 4 associated with La Niña +SAM and deep Amundsen Sea Low

- Patterns 8 - 9 associated with El Niño -SAM and Amundsen Sea high-pressure

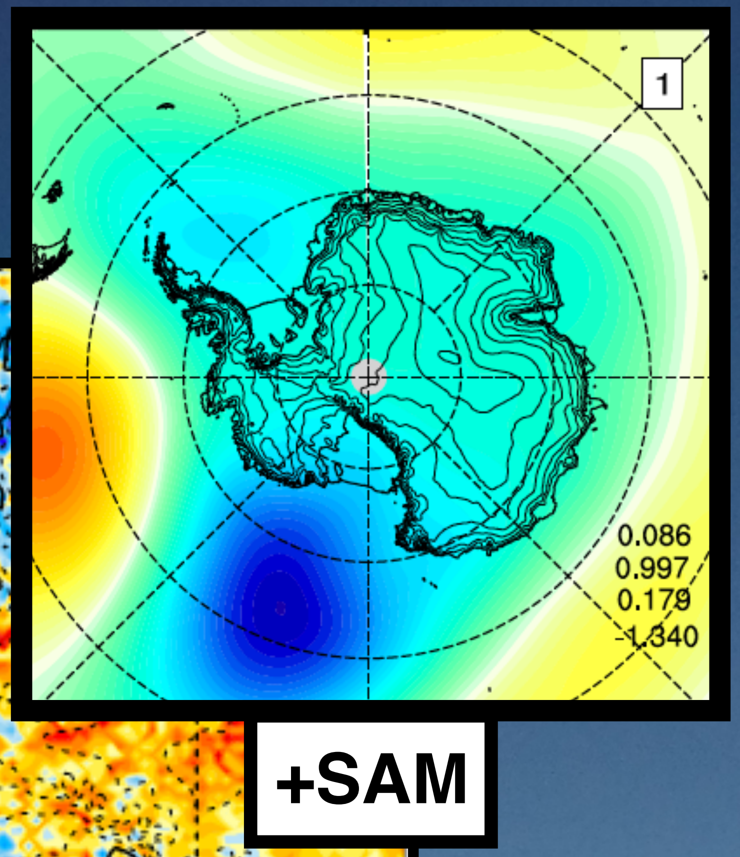
- <u>Combine each synoptic pattern with</u>

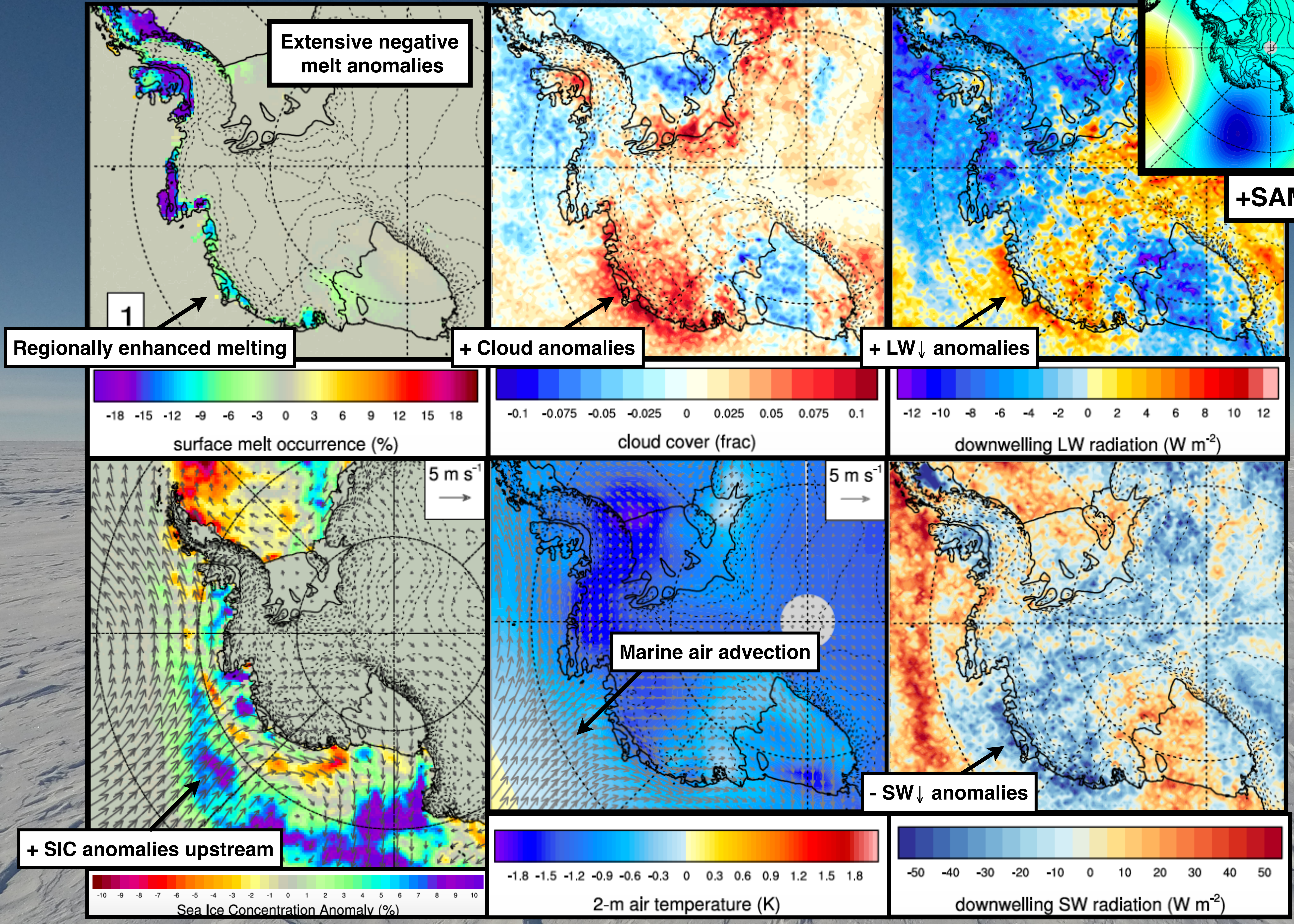
- Surface melt occurrence NSIDC
- Cloud and radiation flux APP-x
- Surface temperature, wind ERA-Interim
- Sea-ice concentration NSIDC

...to diagnose physical processes linking large-scale circulation to surface melt

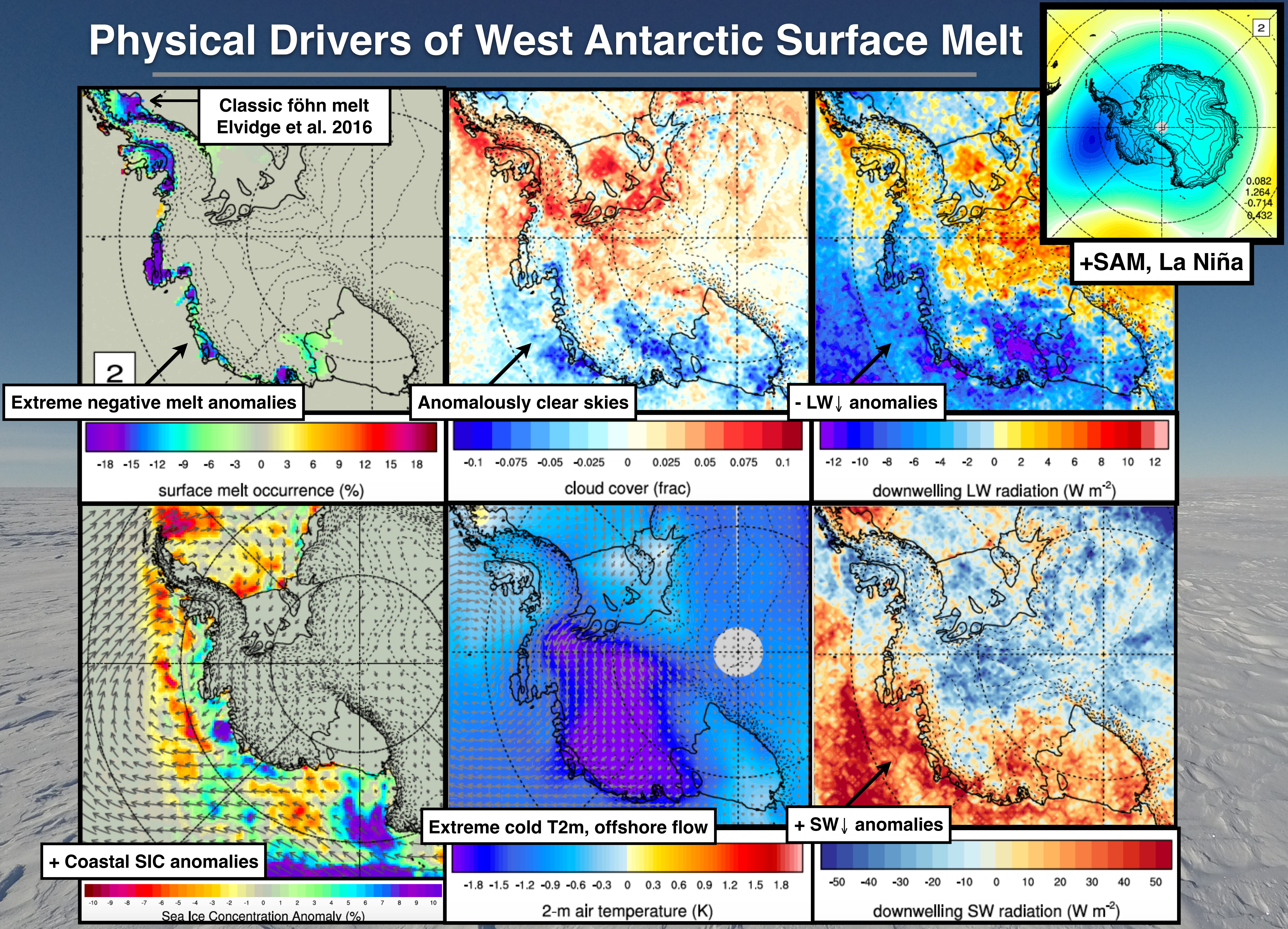


Physical Drivers of West Antarctic Surface Melt

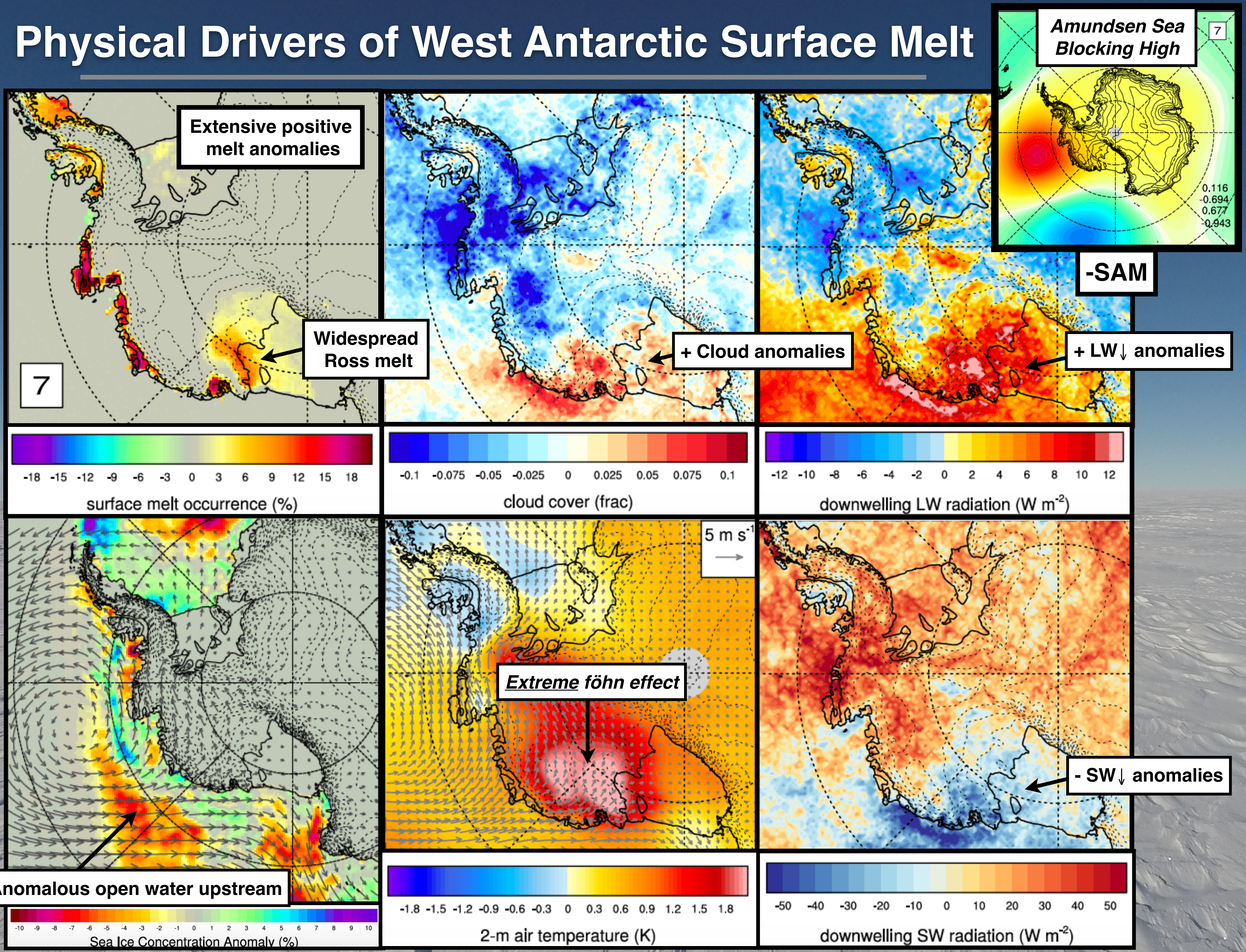




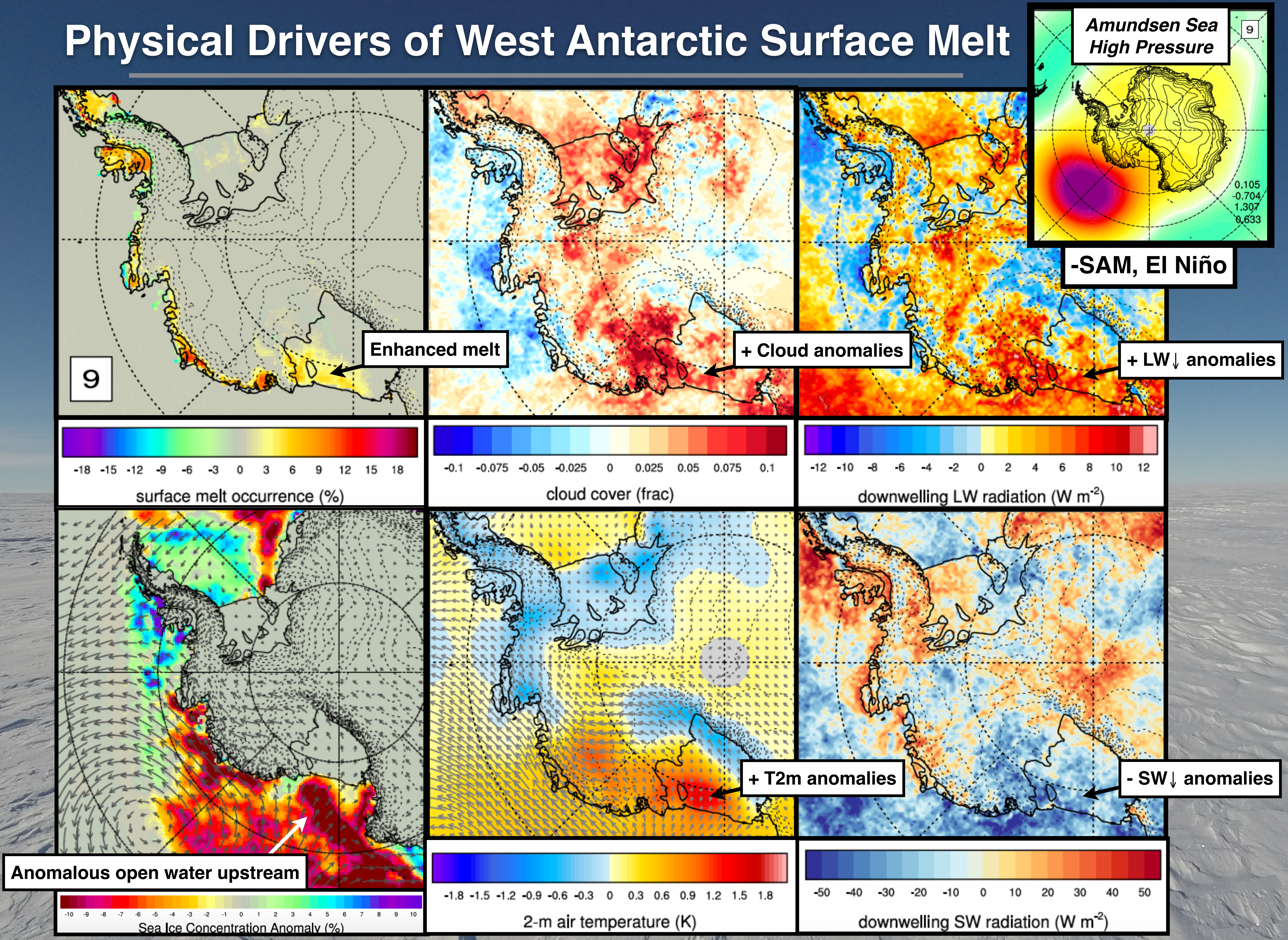
Physical Drivers of West Antarctic Surface Melt



Physical Drivers of West Antarctic Surface Melt

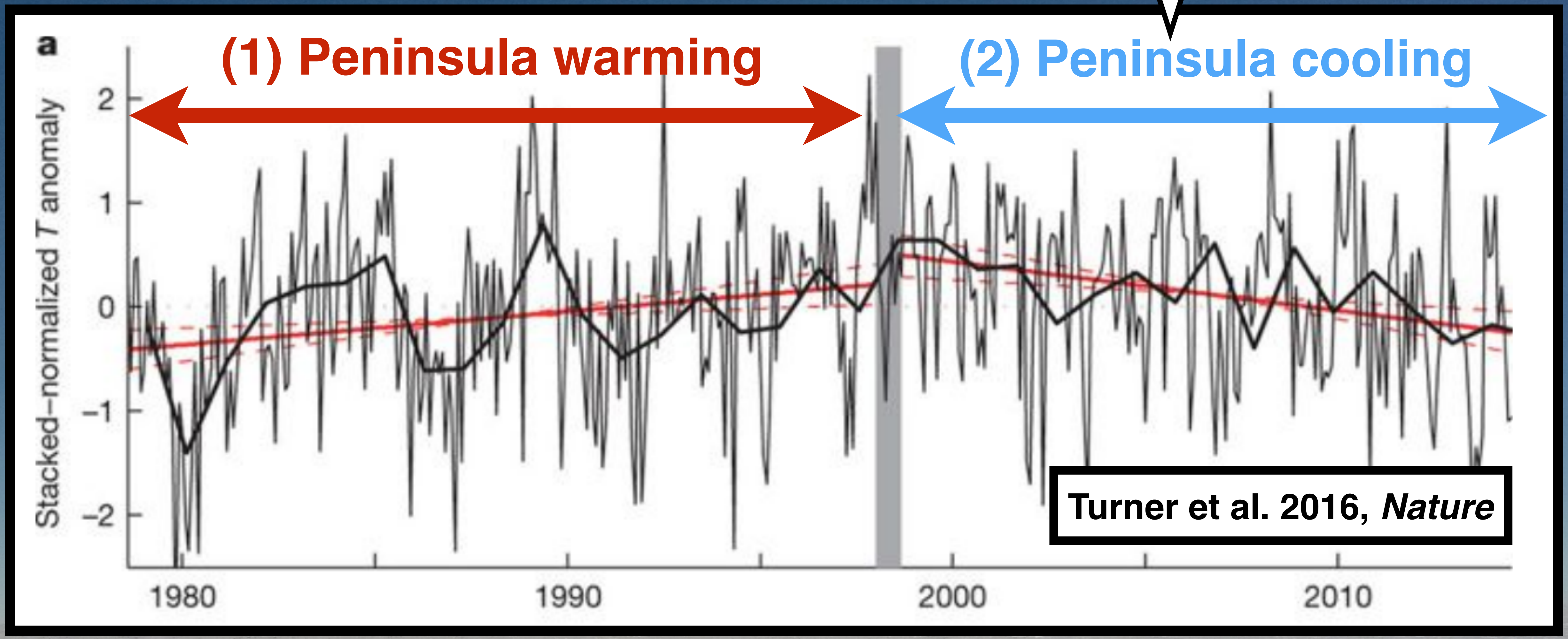


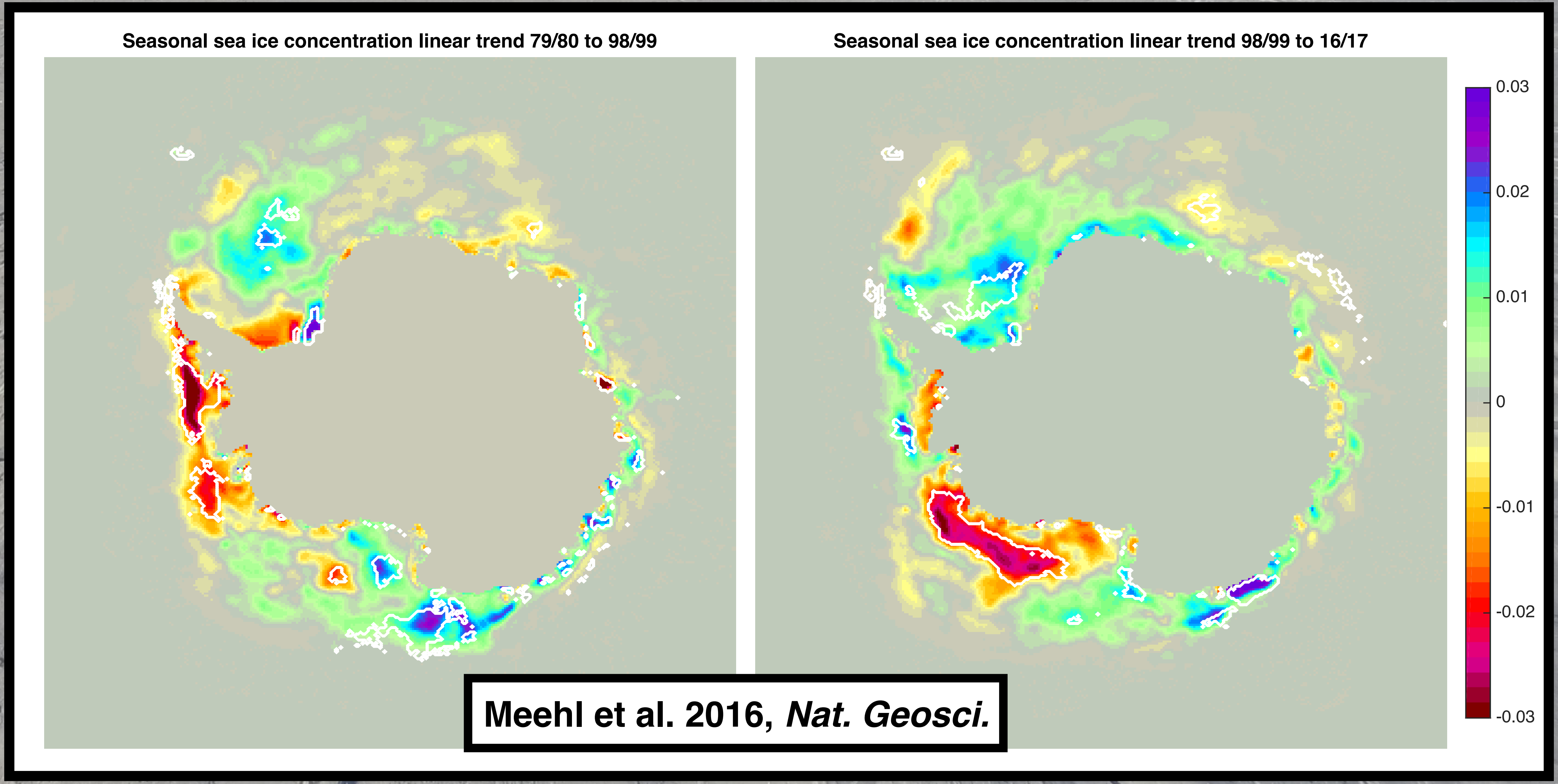
Physical Drivers of West Antarctic Surface Melt



How Has the WAIS Climate Changed During the 21st Century?

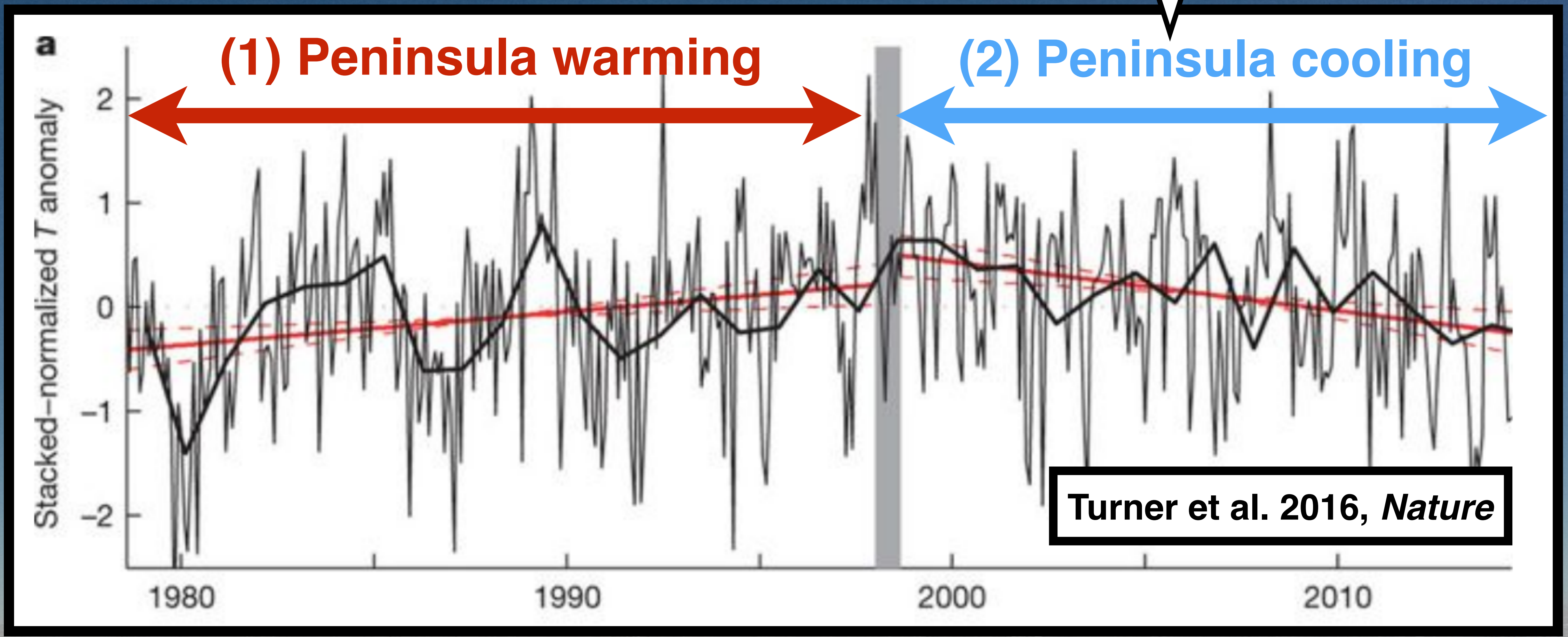
- During the 21st Century…
  - Antarctic Peninsula cooling
  - Sea-ice expansion accelerated

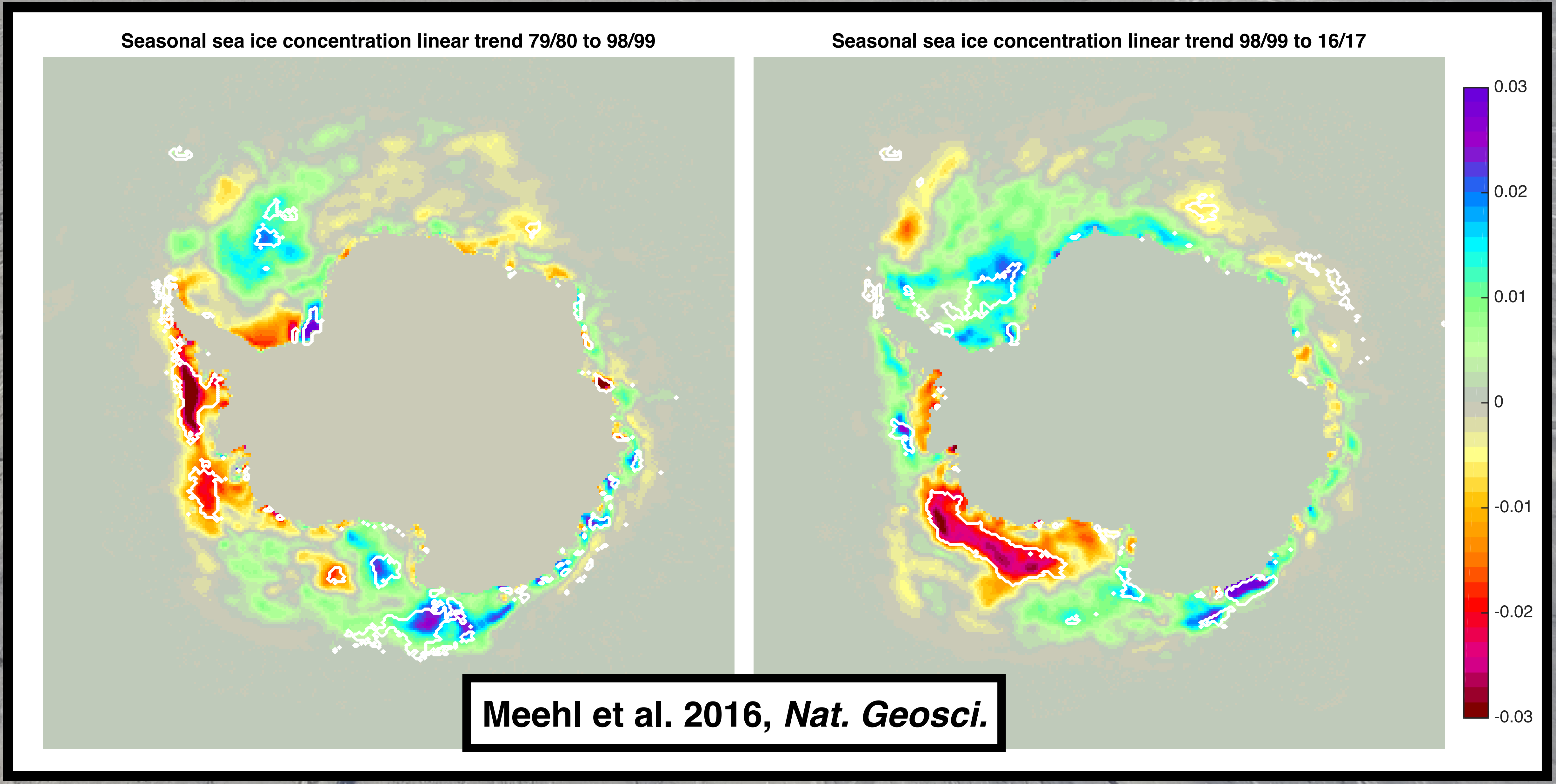




How Has the WAIS Climate Changed During the 21st Century?

- During the 21st Century…
  - Antarctic Peninsula cooling
  - Sea-ice expansion accelerated
- ***What about the WAIS?***

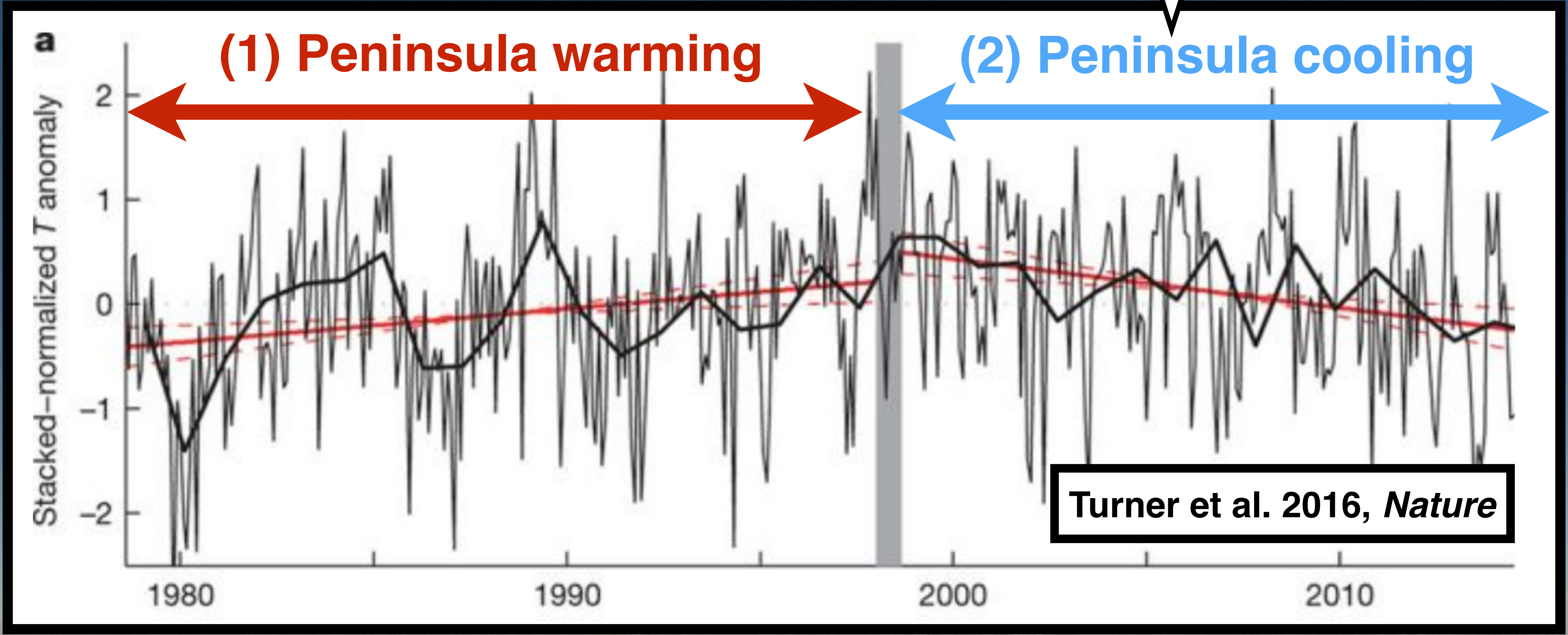


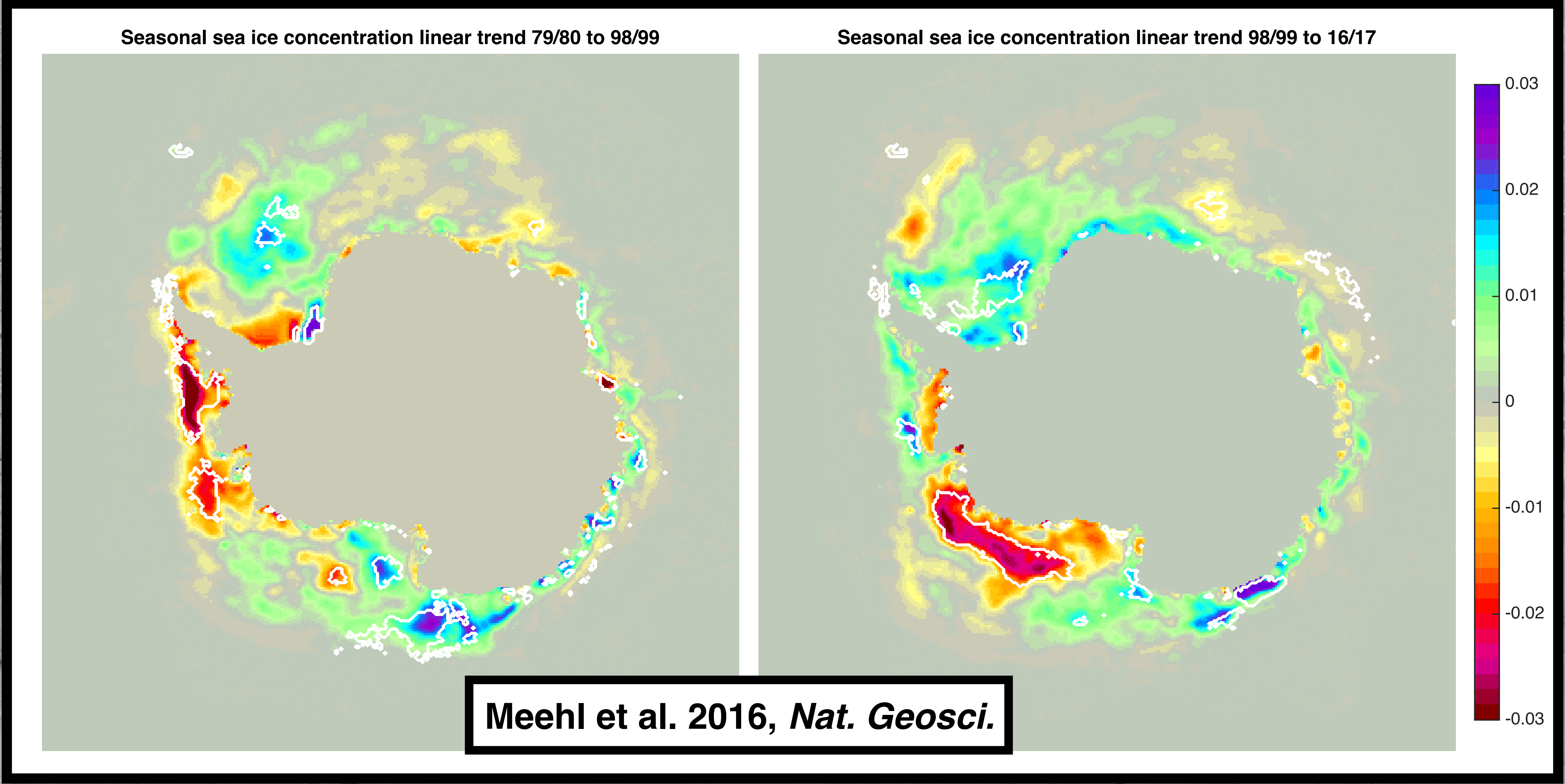


How Has the WAIS Climate Changed During the 21st Century?

- During the 21st Century…
    - Antarctic Peninsula cooling
    - Sea-ice expansion accelerated
- *What about the WAIS?*

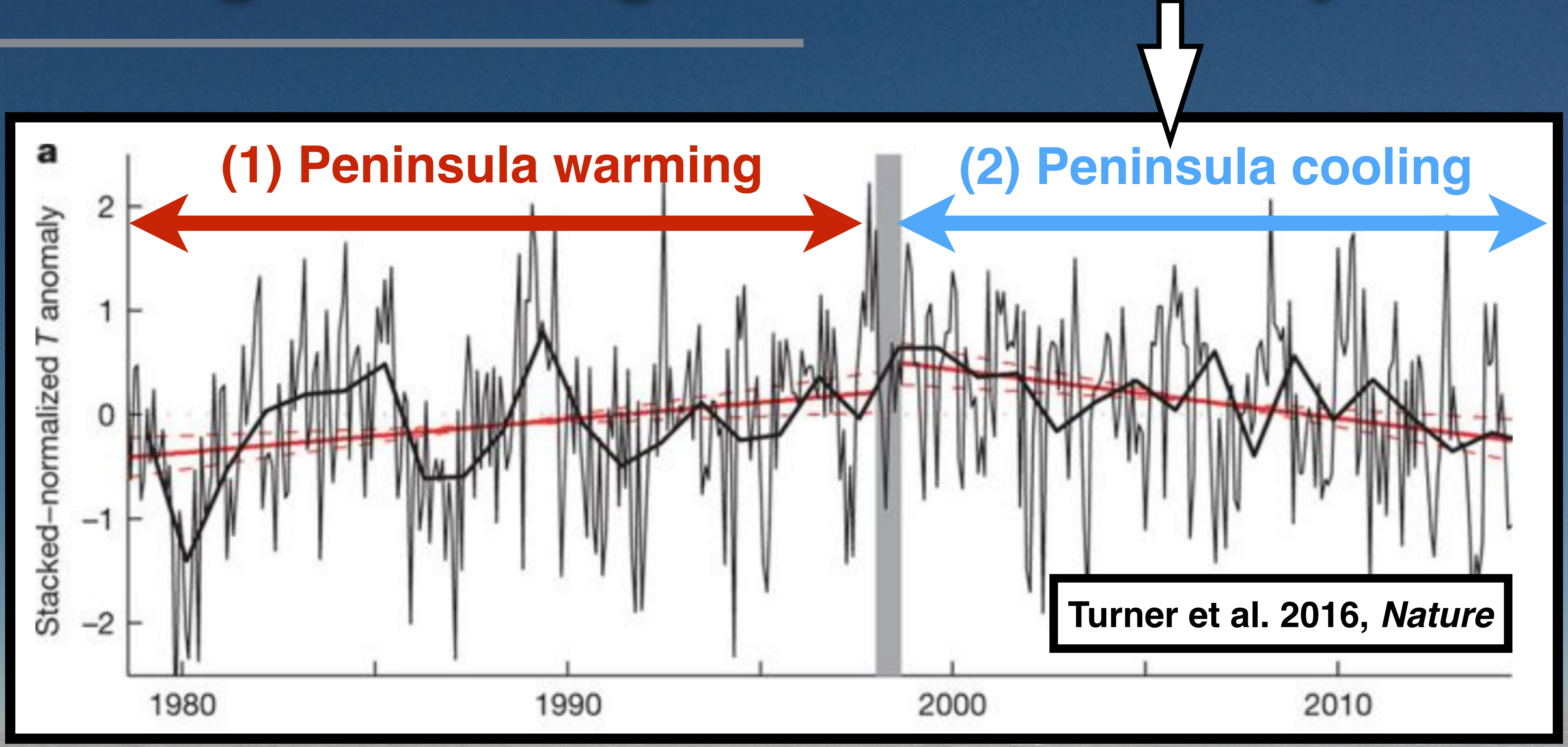
At face value, these trends *suggest* that WAIS has cooled

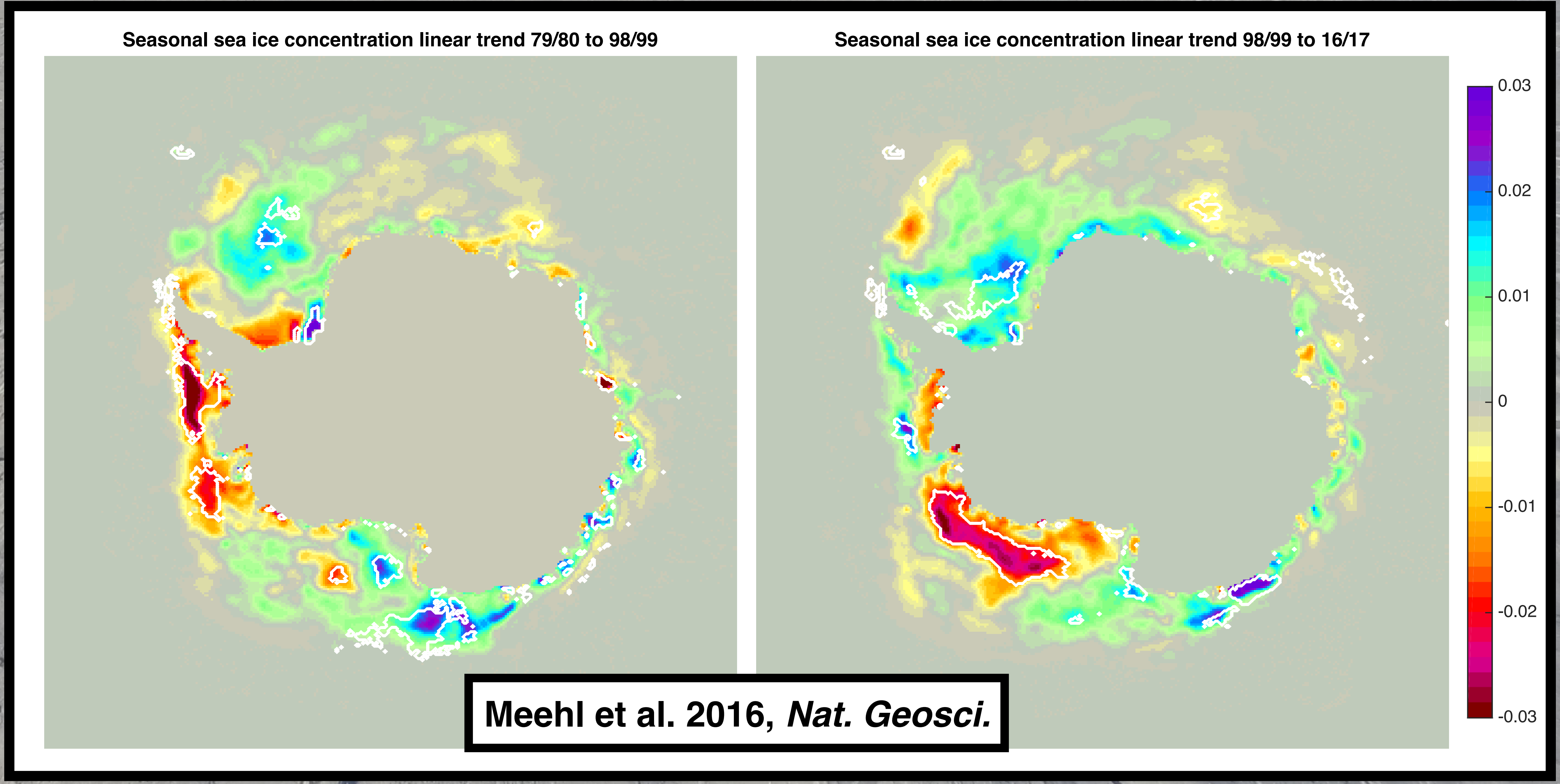




How Has the WAIS Climate Changed During the 21st Century?

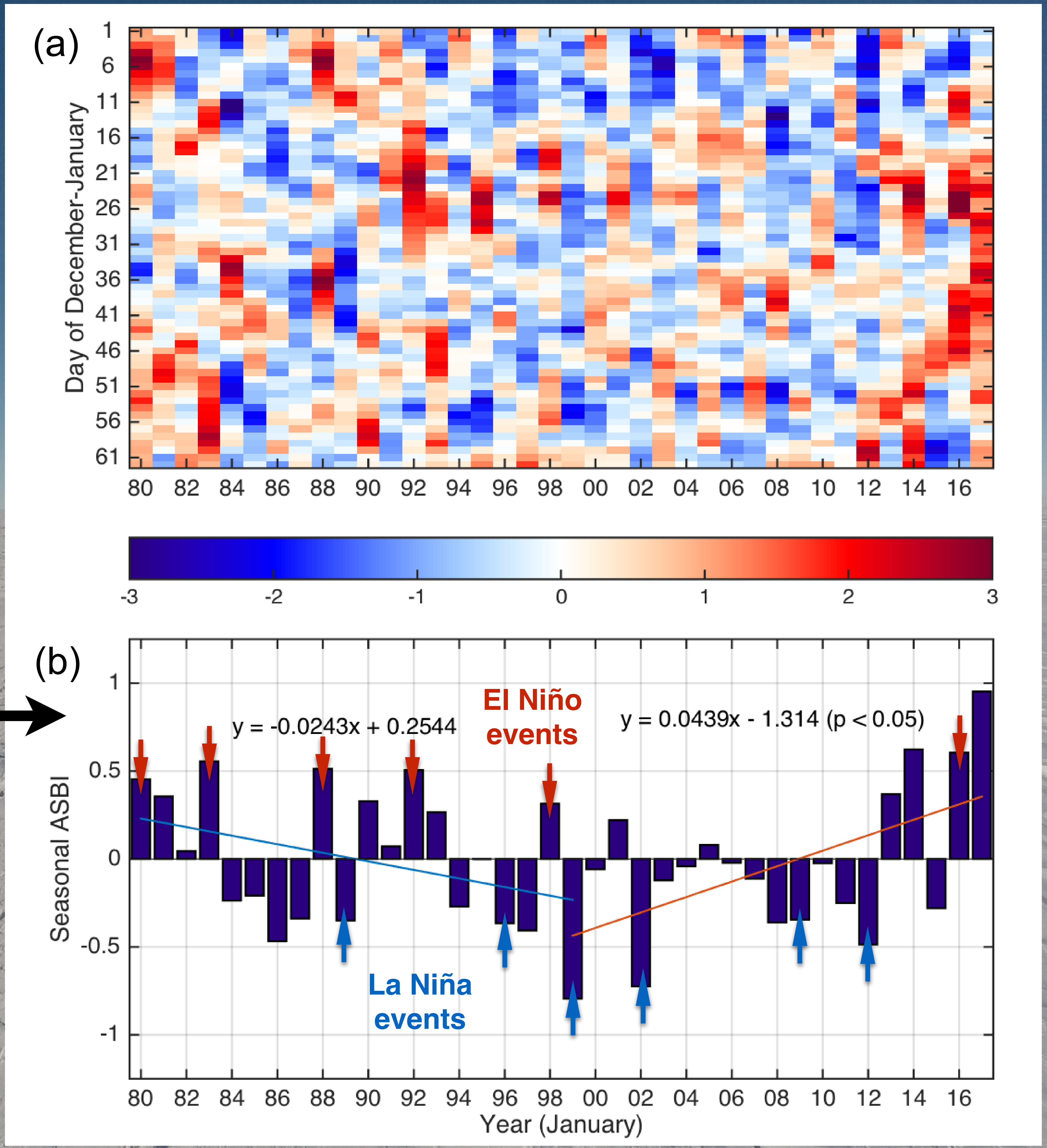
- During the 21st Century…
  - Antarctic Peninsula cooling
  - Sea-ice expansion accelerated
- *What about the WAIS?*
- Preceding analysis: WAIS warming is favored by blocking activity and -SAM
- *How has blocking changed off the coast of West Antarctica?*





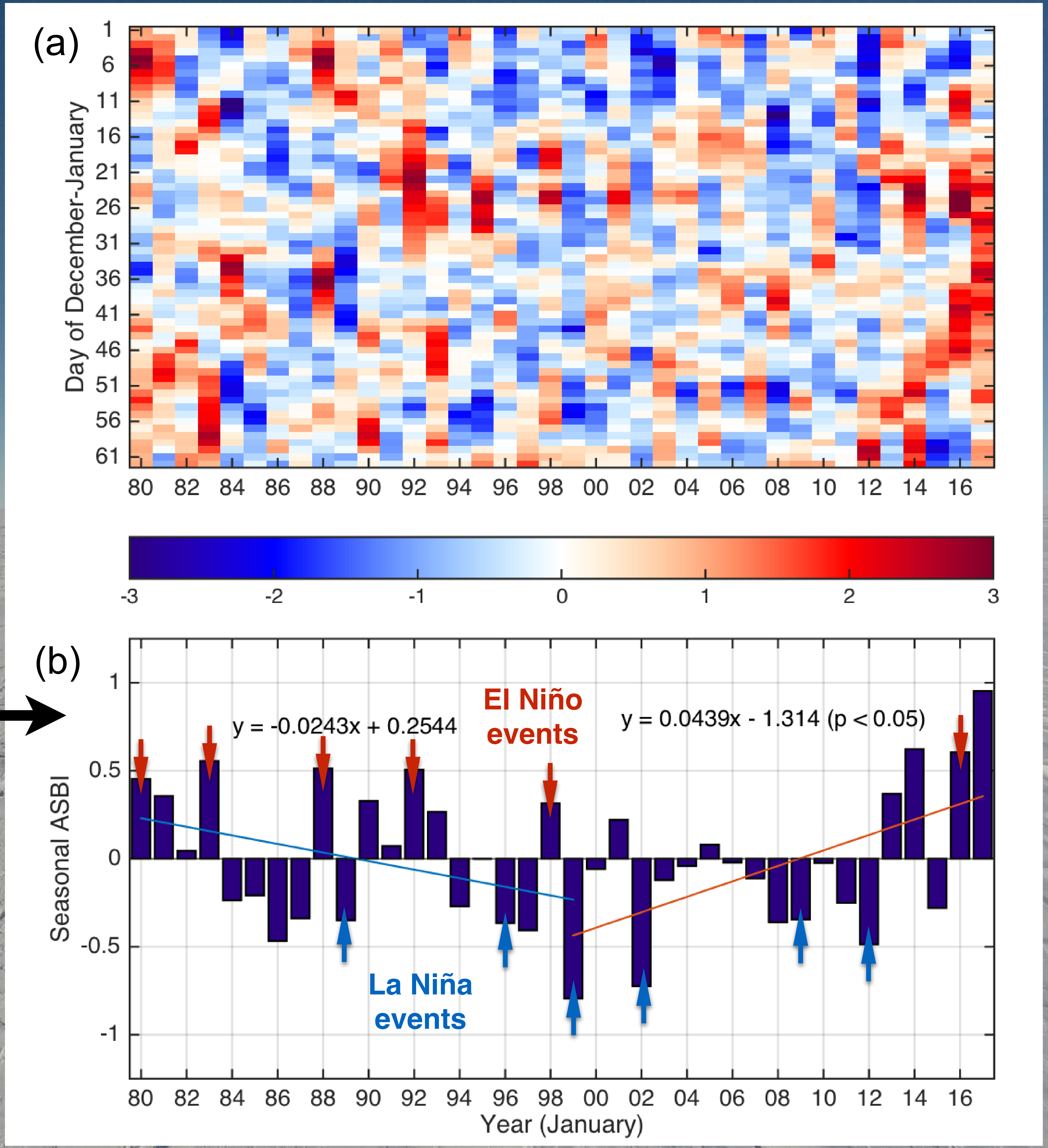
How Has the WAIS Climate Changed During the 21st Century?

- During the 21st Century…
  - Antarctic Peninsula cooling
  - Sea-ice expansion accelerated
- ***What about the WAIS?***
- Preceding analysis: WAIS warming is favored by blocking activity and -SAM
- ***How has blocking changed off the coast of West Antarctica?***
- Amundsen Sea Blocking Index (ASBI):
  - Standardized Z_{700} anomaly over the Amundsen Sea
  - Captures concurrent SAM, PSA variability
  - Correlated with ENSO

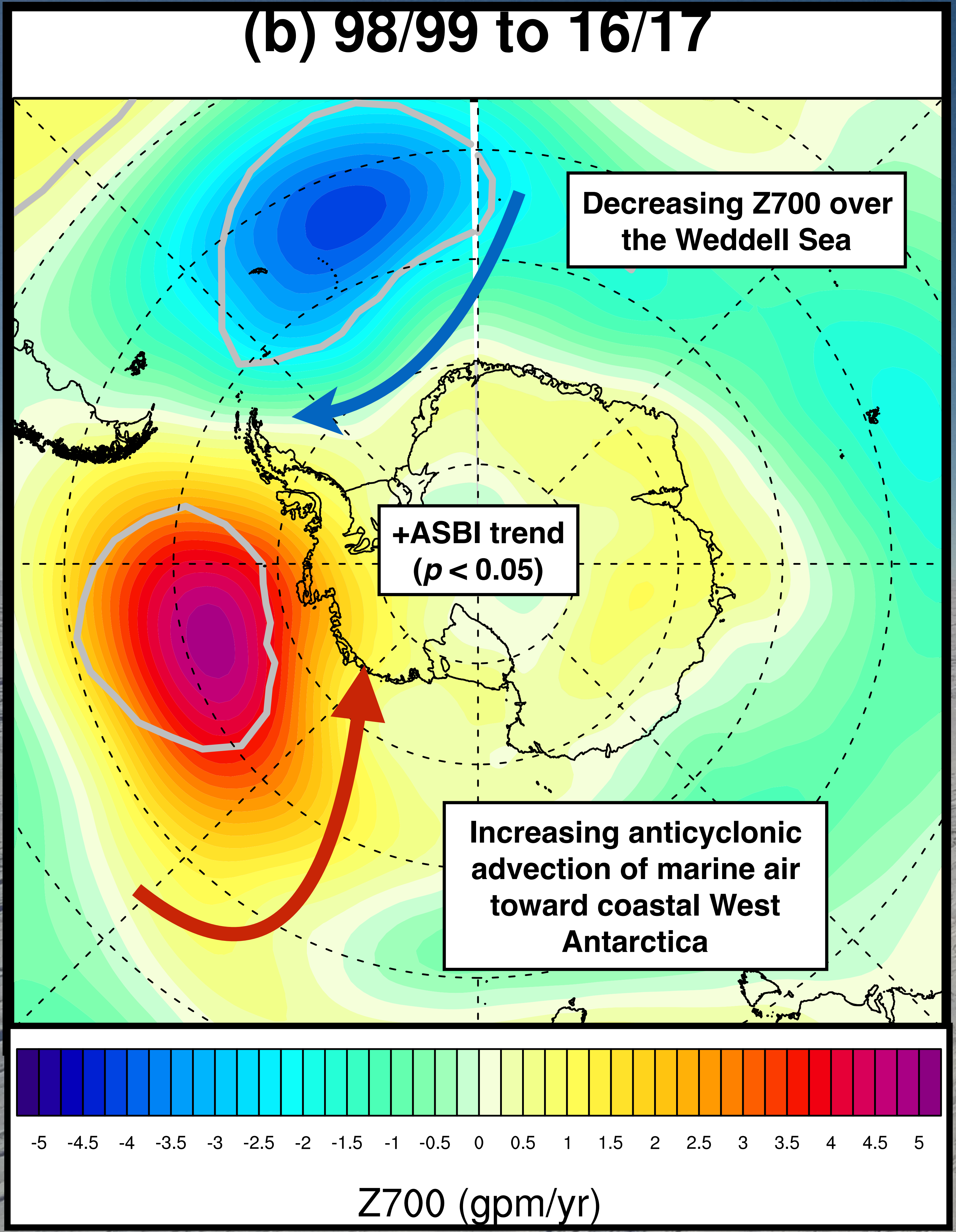


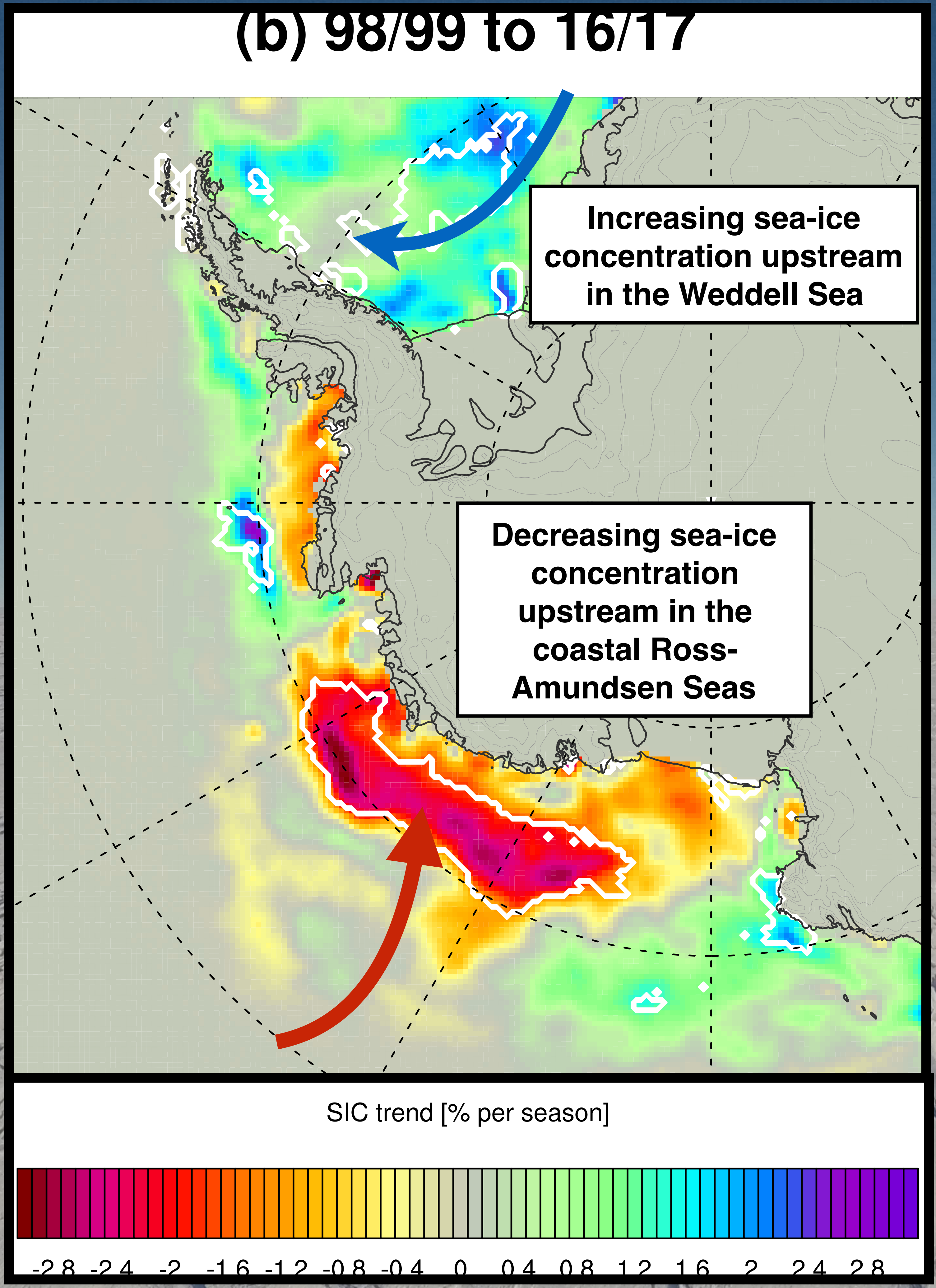
How Has the WAIS Climate Changed During the 21st Century?

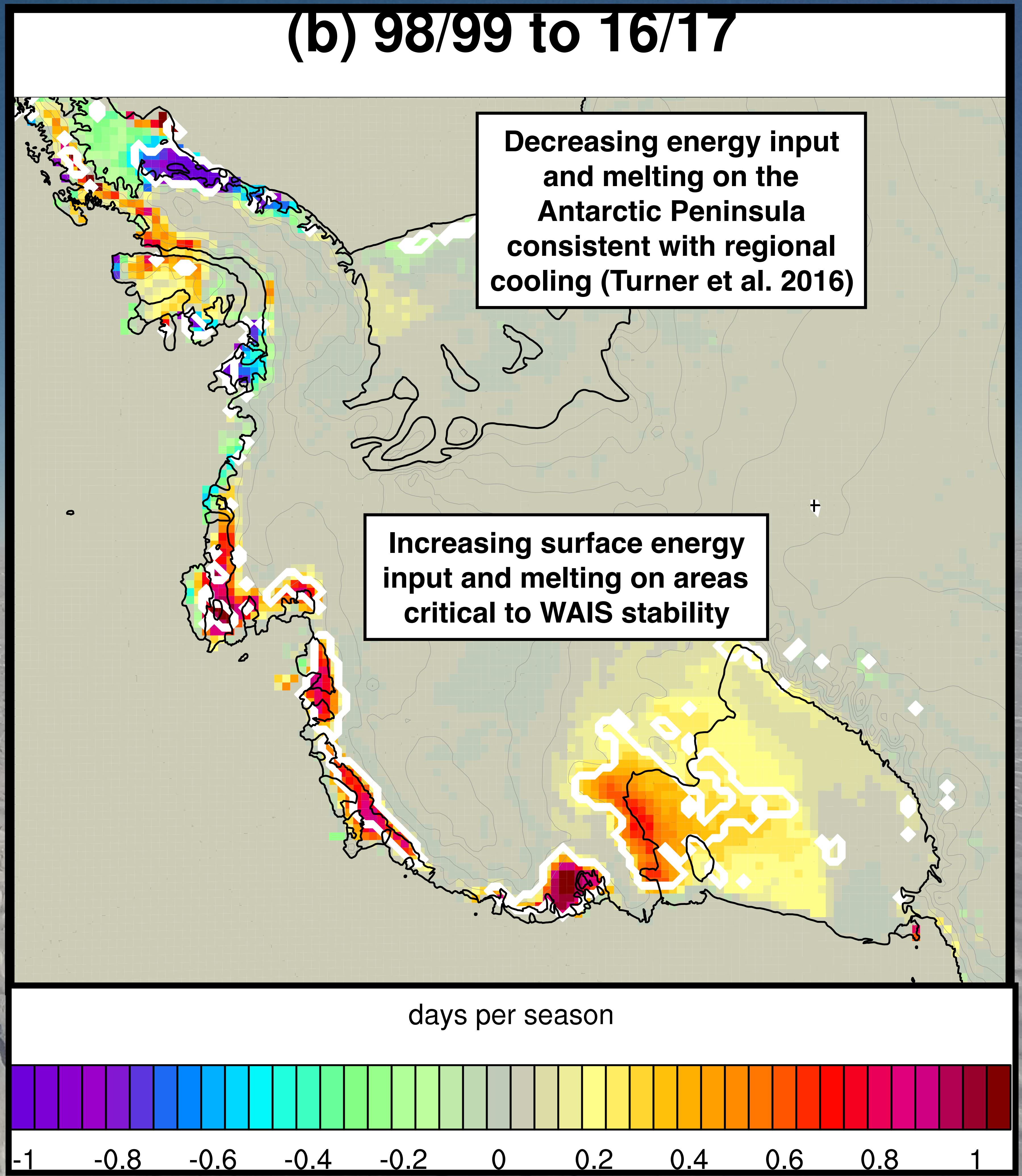
- During the 21st Century…
  - Antarctic Peninsula cooling
  - Sea-ice expansion accelerated
- ***What about the WAIS?***
- Preceding analysis: WAIS warming is favored by blocking activity and -SAM
- *How has blocking changed off the coast of West Antarctica?*
- Amundsen Sea Blocking Index (ASBI):
  - Standardized Z_{700} anomaly over the Amundsen Sea
  - Captures concurrent SAM, PSA variability
  - Correlated with ENSO
- Negative trend from 1979 to 1999: Period 1
- Positive trend from 1999 to 2017: Period 2



21st Century Increase in Coastal WAIS Surface Melt

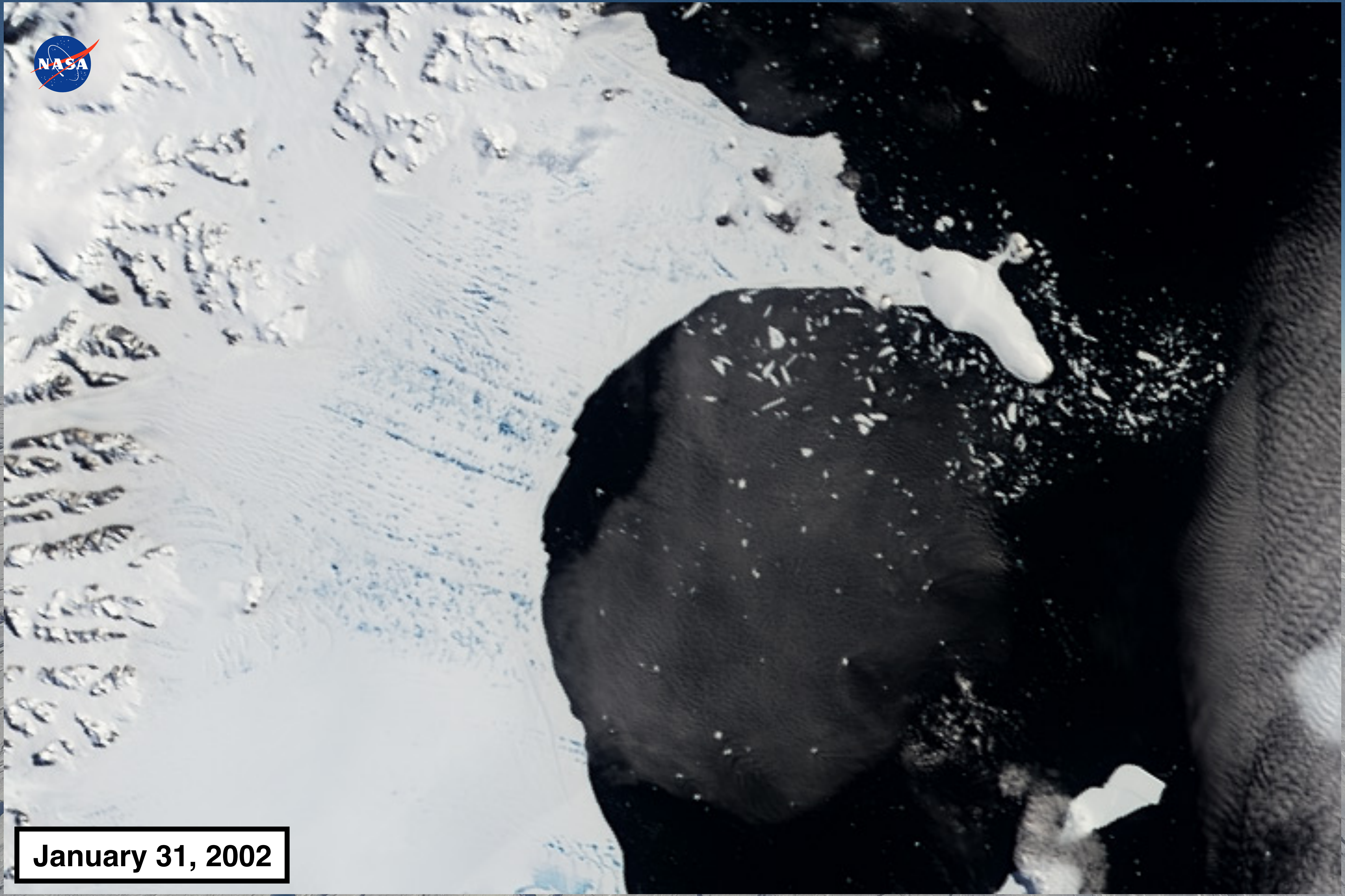




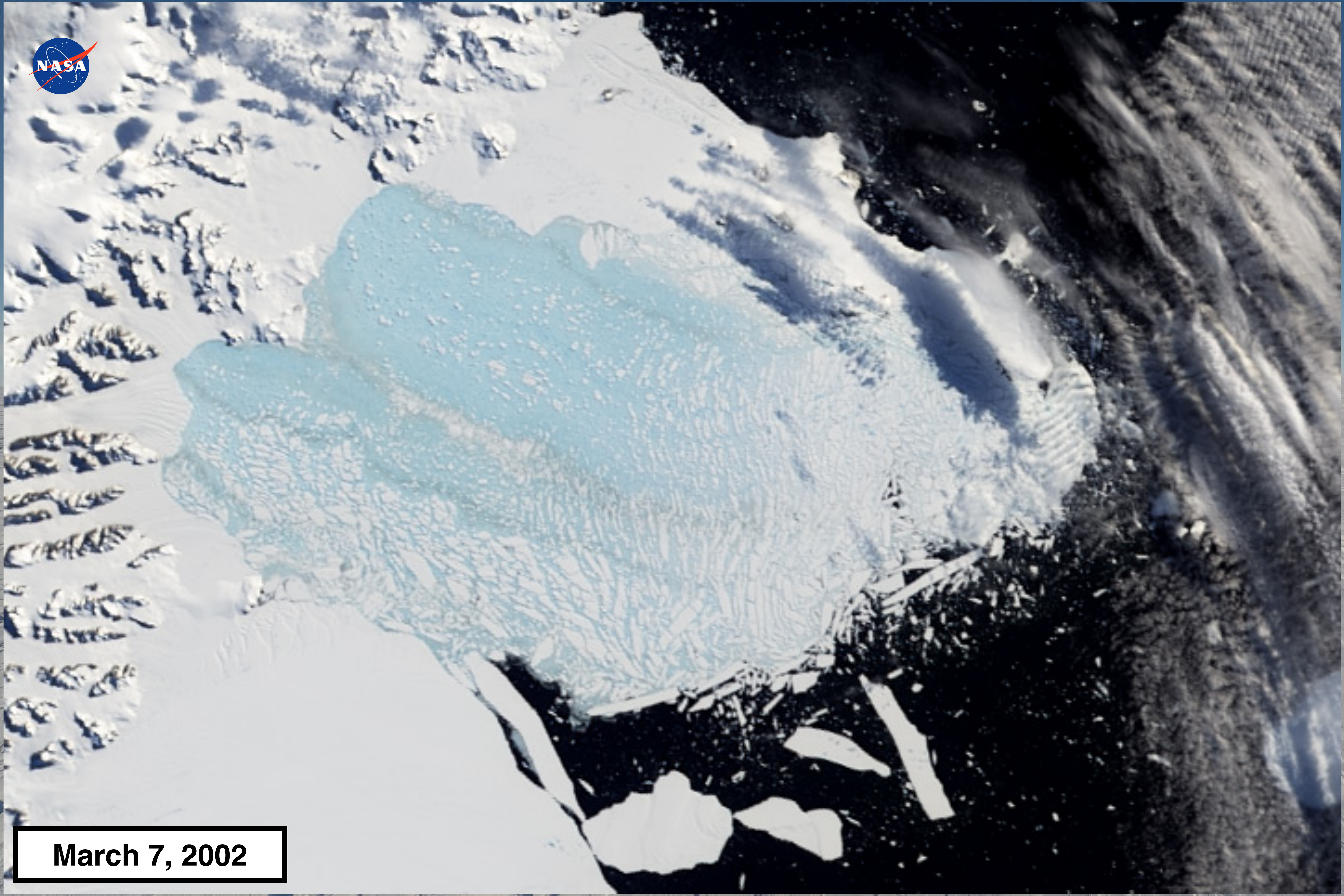


Surface melt trends mirror sea-ice concentration trends, suggesting a common atmospheric forcing and amplification due to increasing air-sea fluxes

Late 20th Century Warming & Melting of the Antarctic Peninsula: Surface Melt-Induced Collapse of Larsen B Ice Shelf

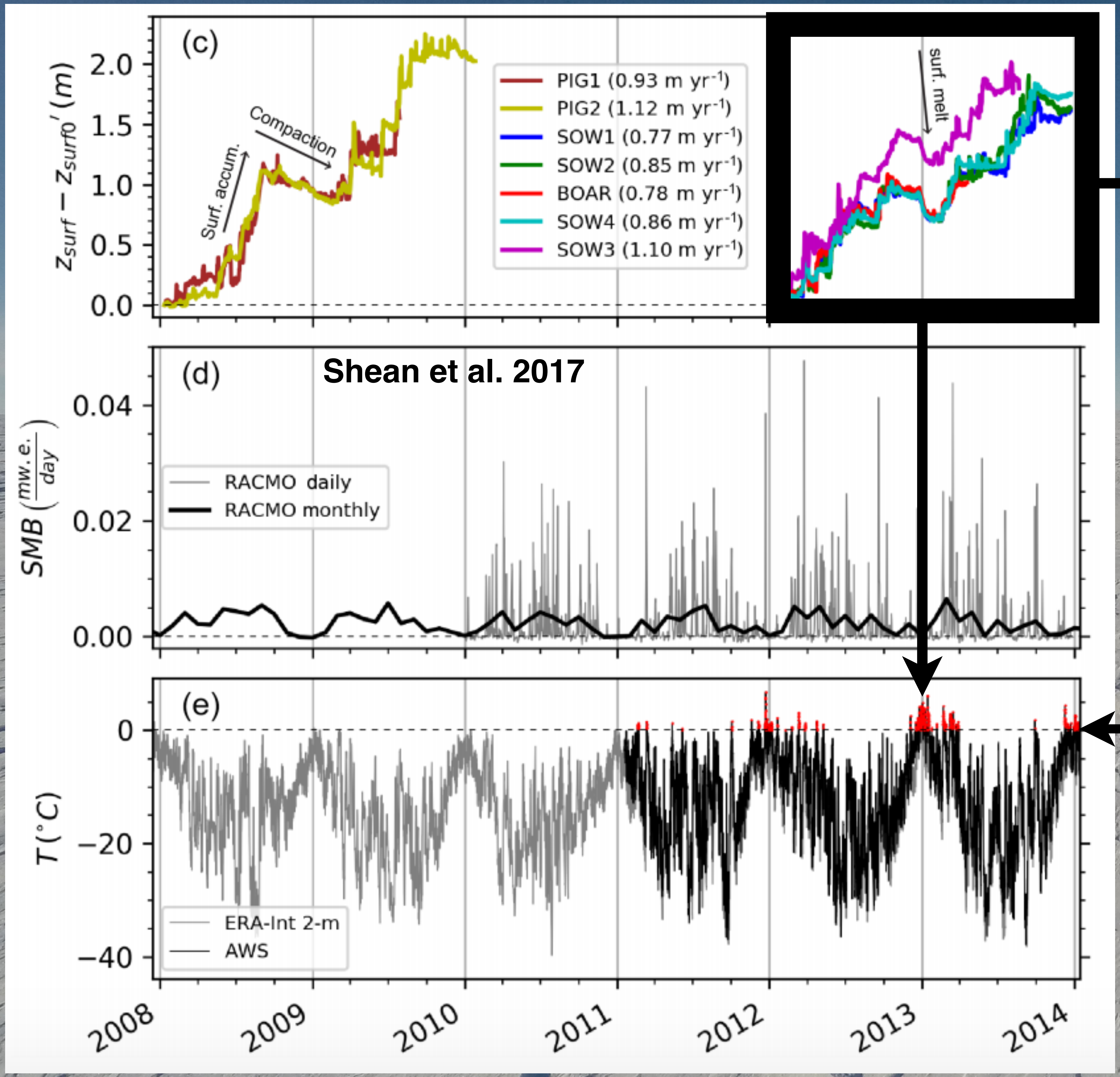


Late 20th Century Warming & Melting of the Antarctic Peninsula: Surface Melt-Induced Collapse of Larsen B Ice Shelf

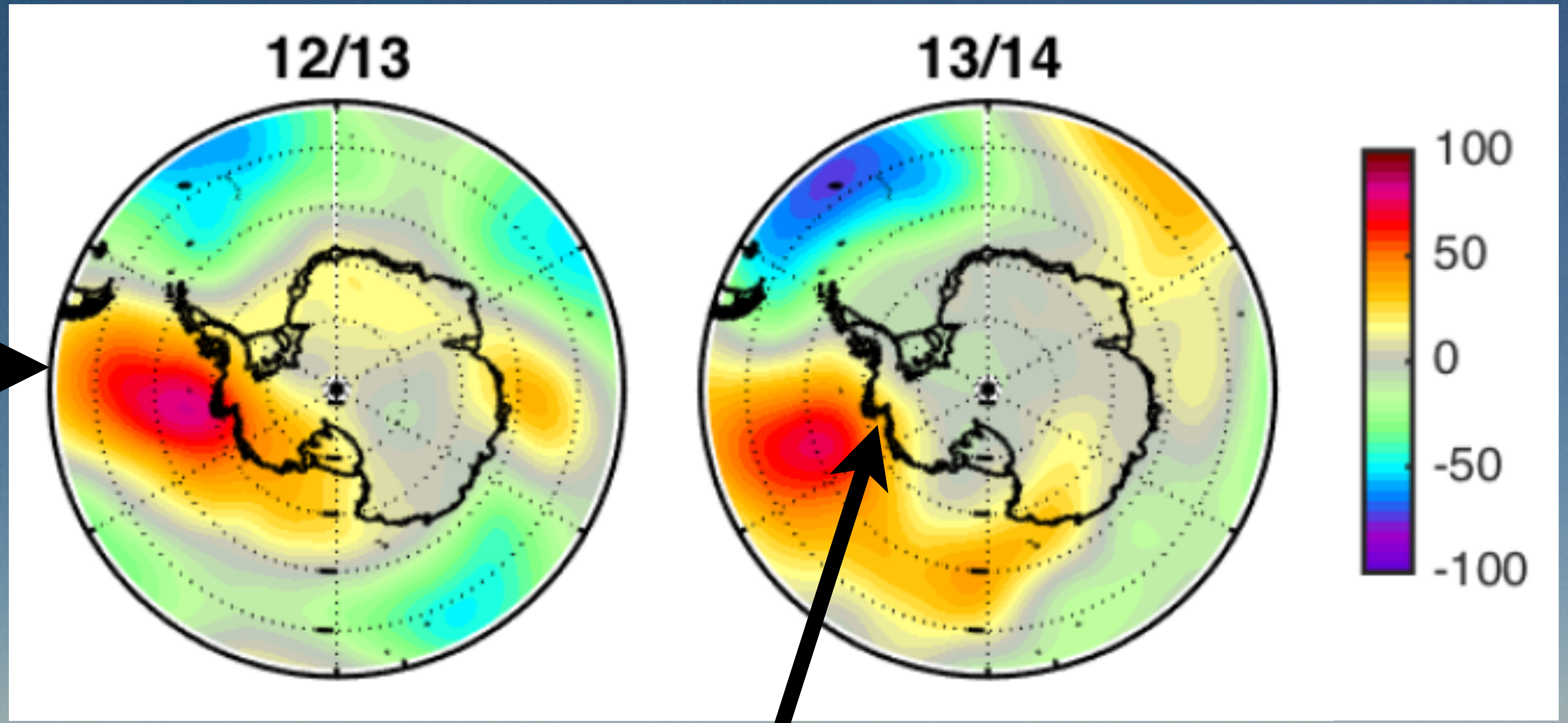


Surface Melt Increase Likely Impacting WAIS Dynamics

GPS units on Pine Island Ice Shelf observed abrupt drop in surface elevation of 0.2-0.3 m in response to warm summer temperatures (1-5°C) in 2012/13

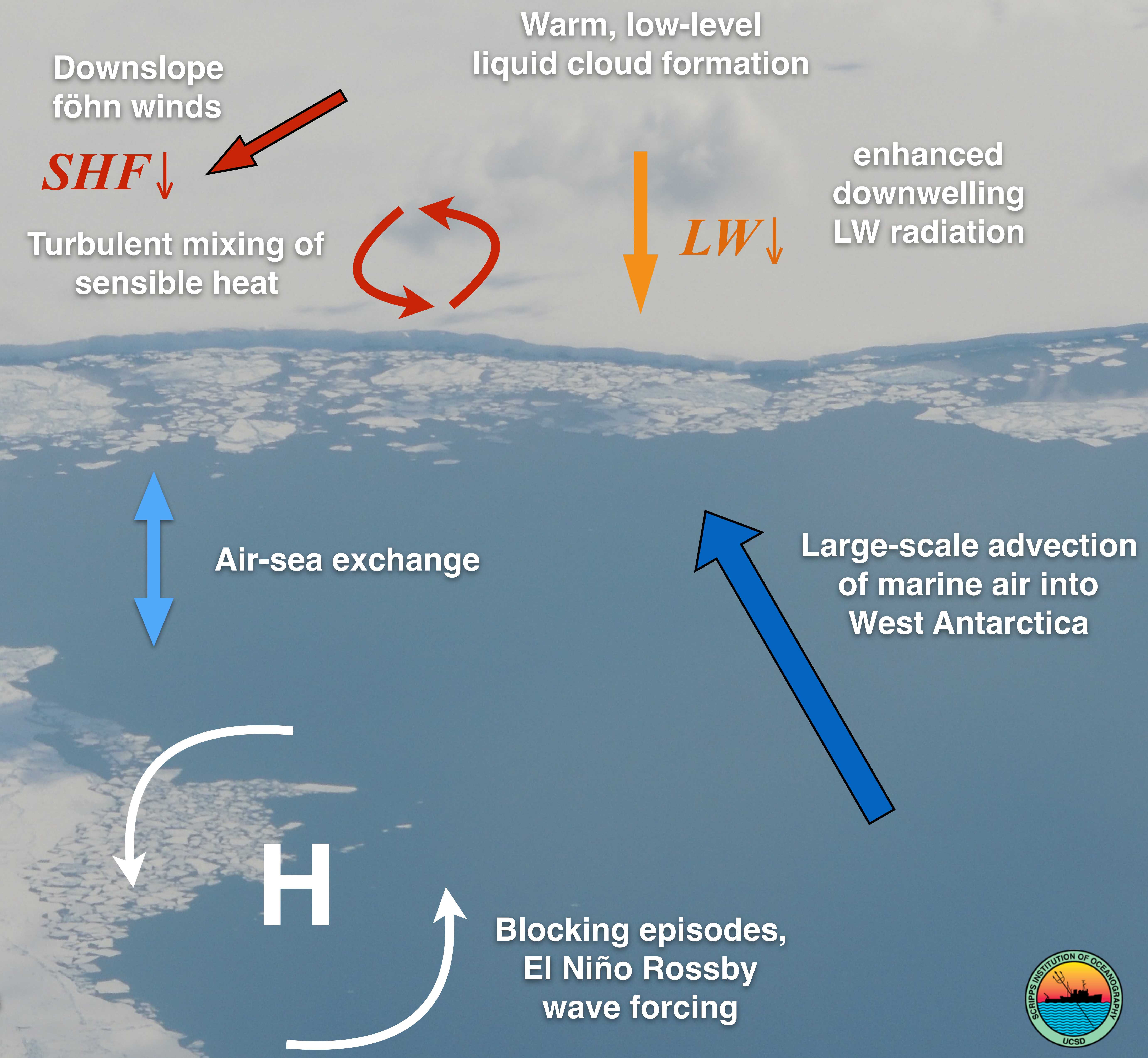


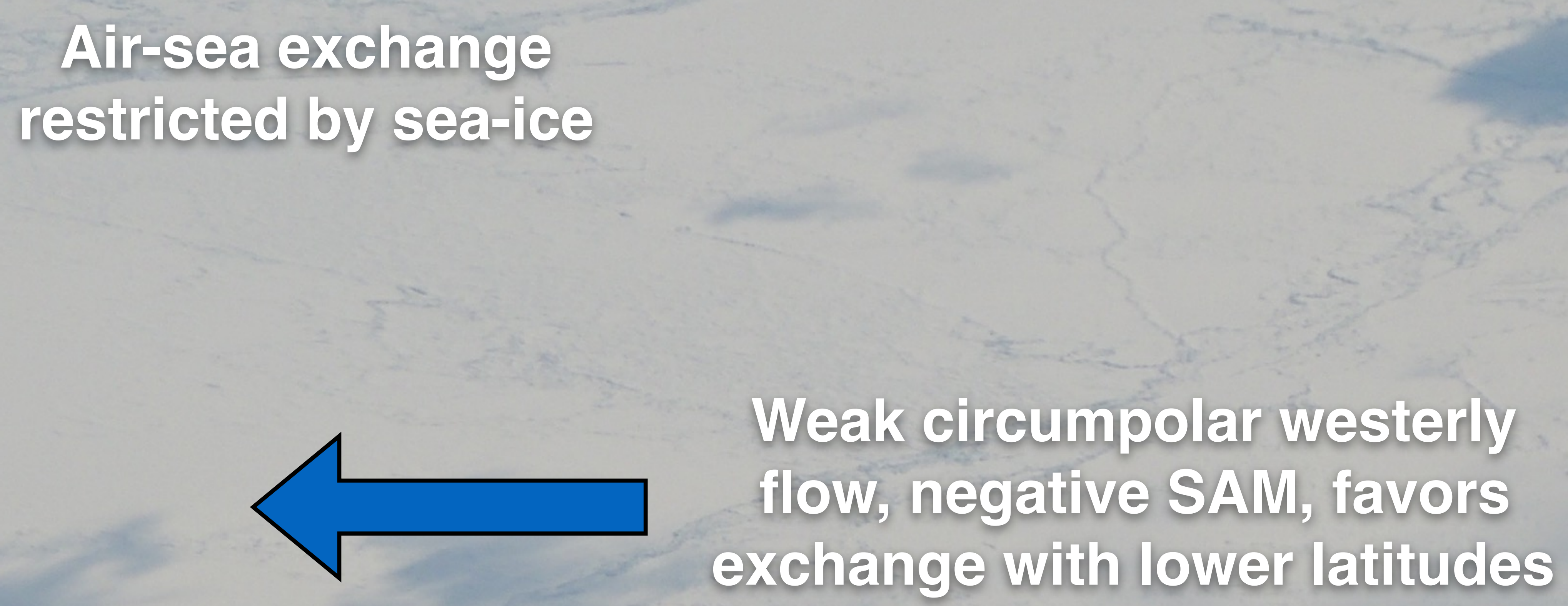
Both seasons characterized by strong +ASBI



Summary

- Since the late 1990s, WAIS surface melt has increased on the Ross-Amundsen sector in response to amplification of the PSA-1 mode and local sea-ice loss
- There is evidence that associated ice-shelf thinning has likely accelerated WAIS mass loss

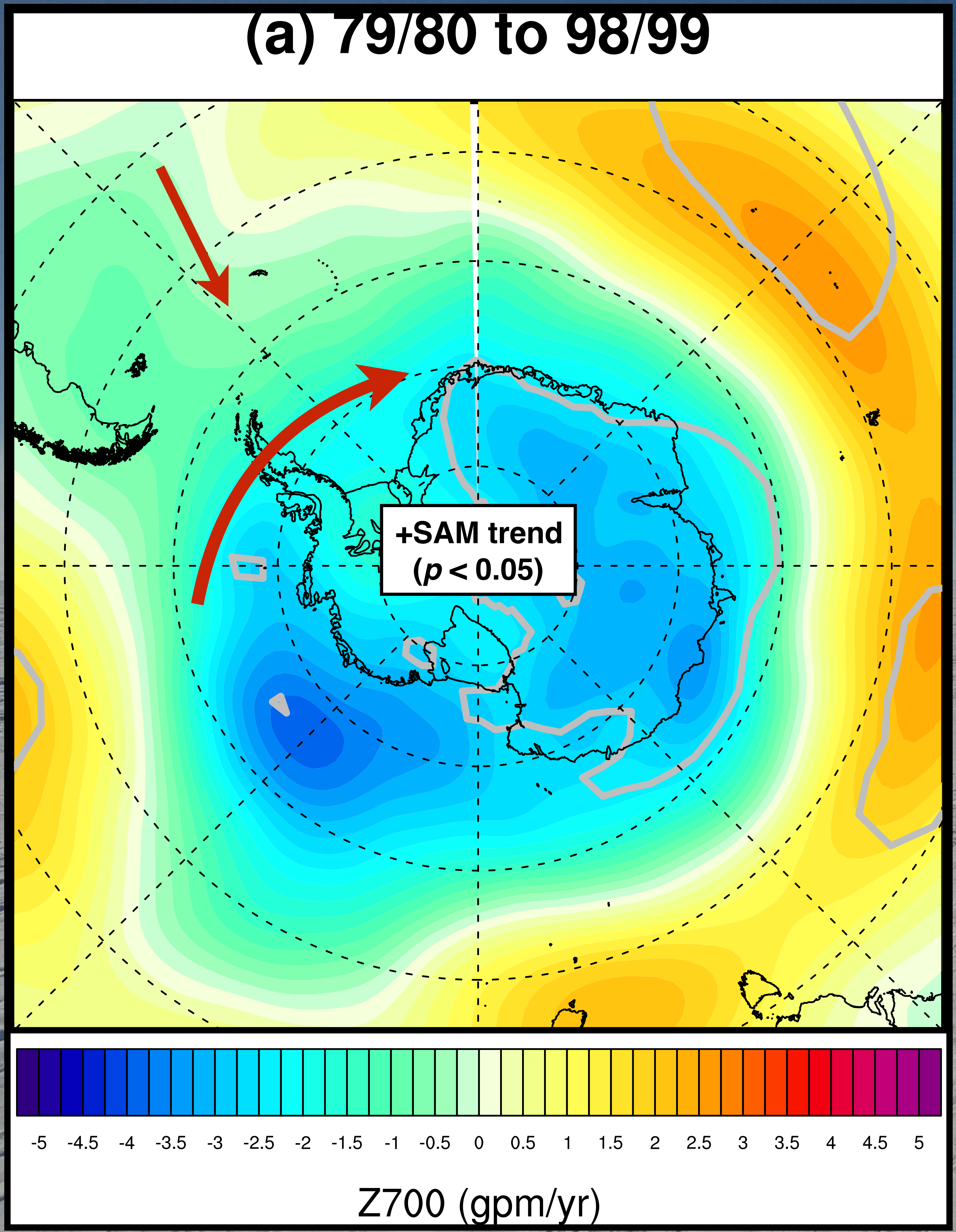


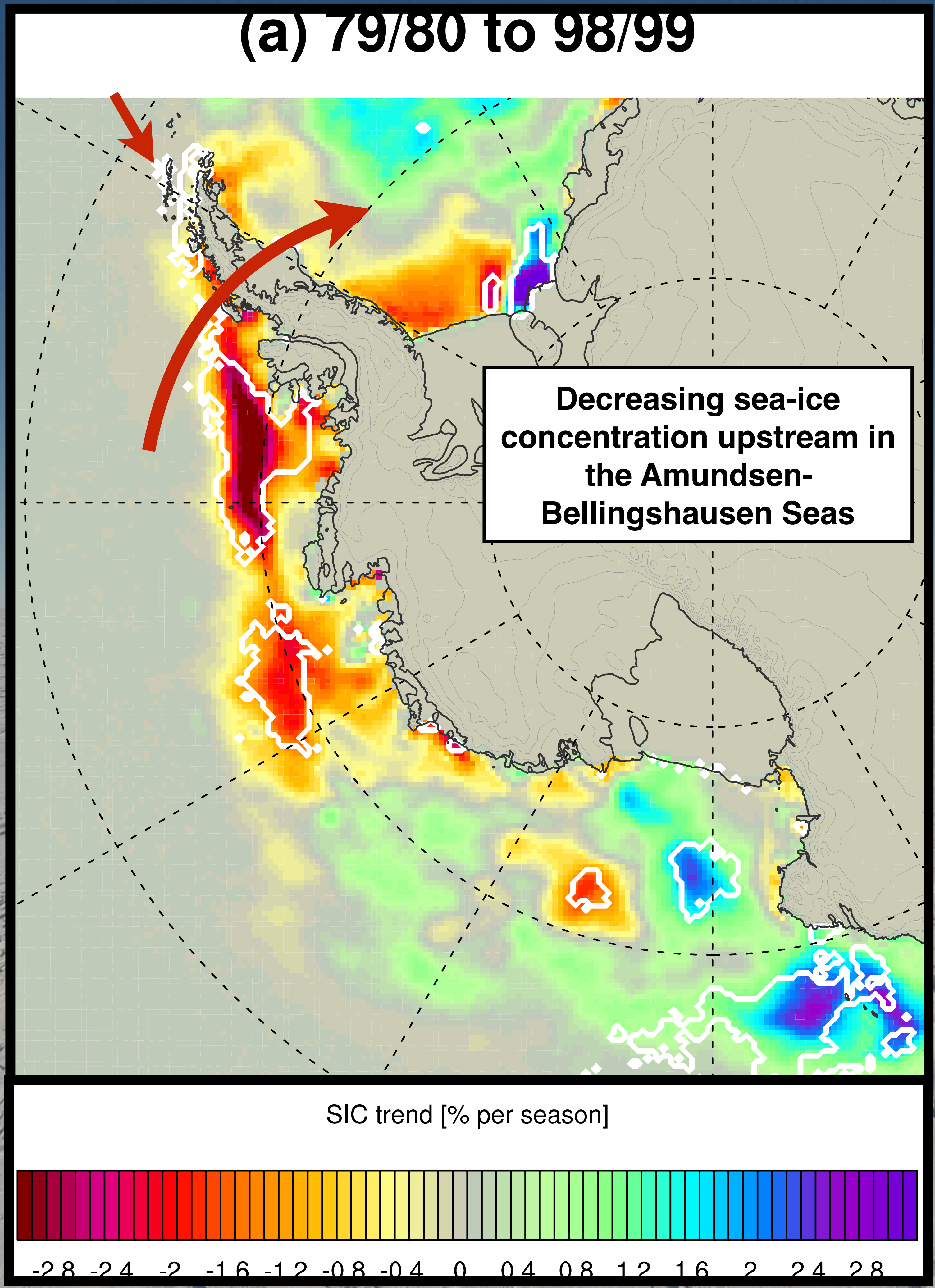


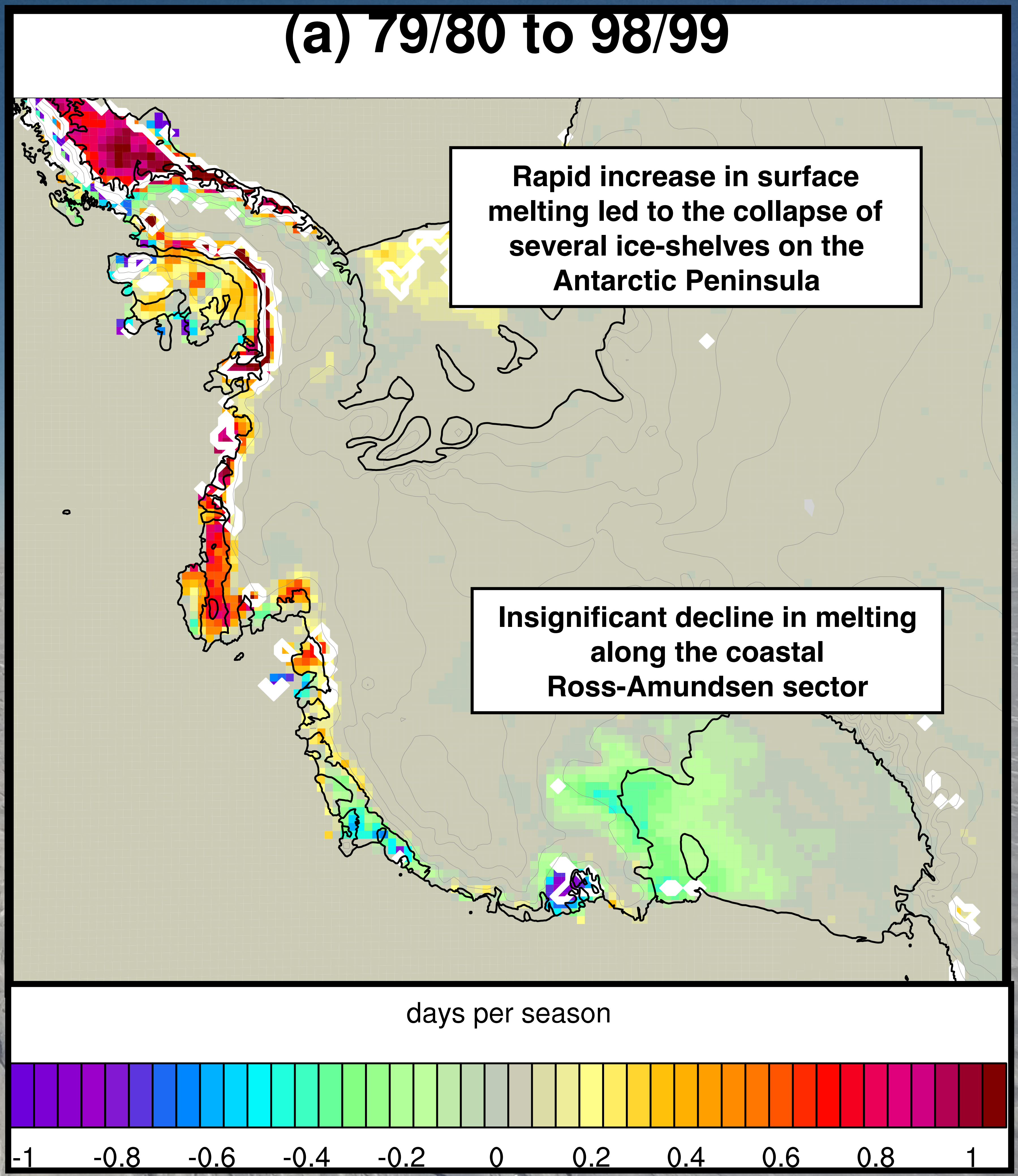

Thank You!
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UCSD

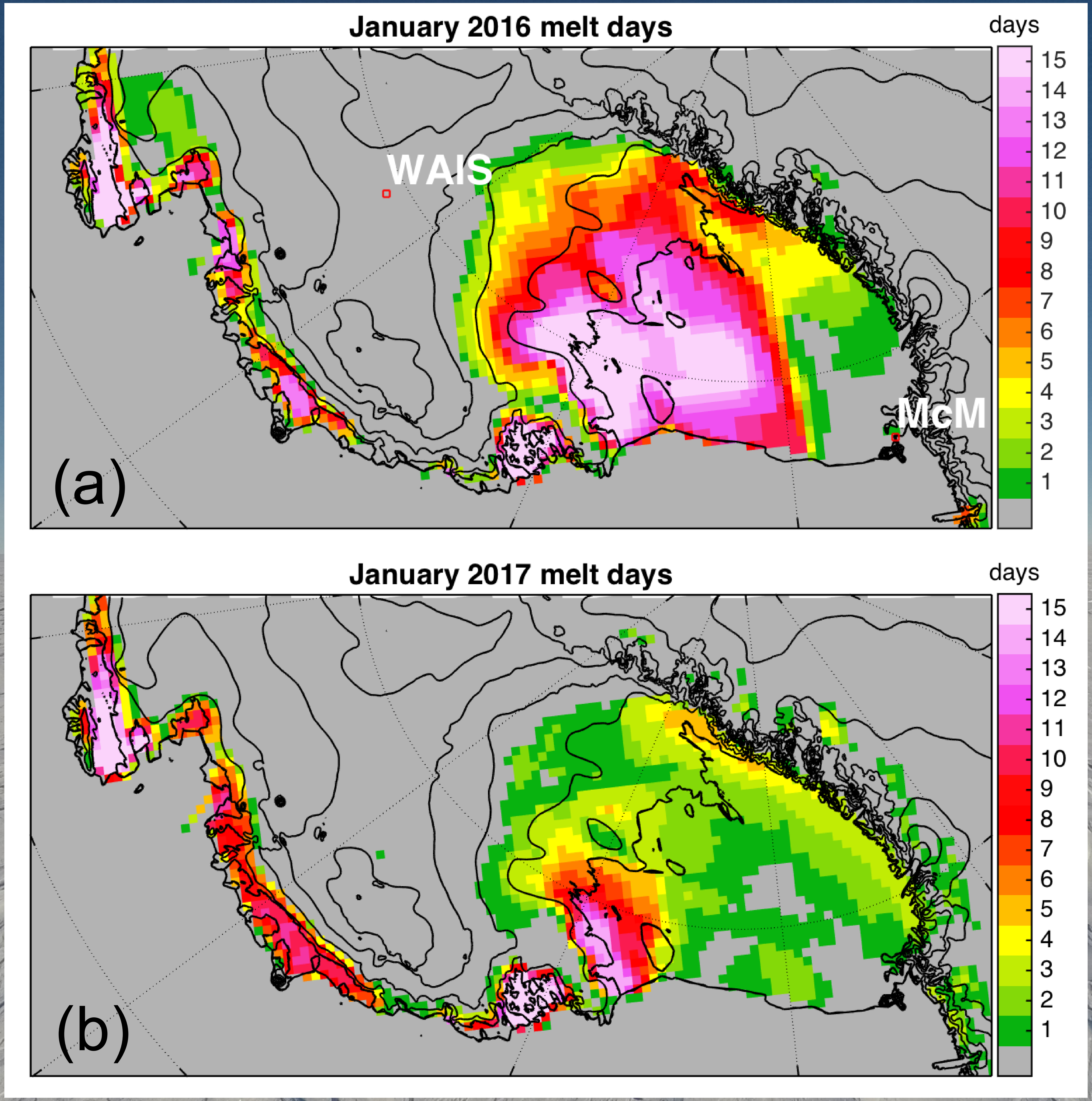

Extra Slides

Late 20th Century Warming & Melting of the Antarctic Peninsula








January 2016 melt days
days
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
WAIS
McM
(a)
January 2017 melt days
days
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
(b)